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A study on the influence of thermal water discharge from the Koezienice power plant on thermal regimes and water quality of the Vistula River was carried out between January 1973 and December 1975.

Results of field survey of the thermal plume indicate that under non-extreme conditions of low flow and full capacity operation (1) the maximum stretch influence of heated water was 50 km and (2) theoretical models for estimating average temperature of cross-sections downstream are adequate.

The influence of thermal water discharge on water quality was small and shown mainly by decrease in dissolved oxygen and increase in nitrite concentration. Data are presented on effects on biochemical processes and size distribution of fine suspended sediments. Formula are developed to determine permissible river temperatures to meet dissolved oxygen criteria.

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EFFECTS OF THERMAL DISCHARGES ON PHYSICO - CHEMICAL PROCESSES AND WATER QUALITY

VISTULA RIVER, POLAND

by

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RESEARCH GRANT No. PR-05-532-5

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report presents the results of a cooperative study by the Institute of Meteorology and Water Management of Poland under the Special Foreign Currency Program, PL-480.

The objective of this study was to determine the influence of thermal discharges from an electric power plant on the physical, chemical and biochemical processes occurring in the receiving river and the effects on water quality.

A. F. Bartsch
Director, CERL

ABSTRACT

The study on the influence of thermal water discharge from the Kozienice power plant on the thermal regimes and water quality of the Vistula river has been carried out. Kozienice power plant is situated at the 425th km of Vistula river.
The first unit started its work in November 1972.
The construction of the power plant was finished in February 1973 when the plant reached the capacity of 1600 MW.
The plant is operating with open cooling system using Vistula water.

The research was performed in the period from January 1973 to December 1973.
The thermal study carried out downstream of the Kozienice power plant included:

- expedition type of survey. The temperature and velocity distributions in chosen cross-sections of the river and in the outlet channel were done.
- periodical type of survey. The temperature and velocity distribution in the cross-section 1000 m downstream of the discharge and in the outlet channel.
- Everyday observations of the temperature in the three cross-sections at three points in each both banks and midstream at 7 a.m., 12 noon and 6 p.m.

On the basis of the field survey results it has been stated:

- No extreme conditions (i.e. maximal natural water temperature, low flow and full capacity of power plant) occured during the project duration.
- The maximum length of the river stretch under the influence of the heated water was equal to 30.0 km.
- The theoretical study has shown good applicability of theoretical models for evaluation of the average water temperature in a river cross-section downstream of the heated water discharge.

The physical and chemical investigations of Vistula water were carried out on the distance from Pulawy (54 km upstream of the power plant) to Warsaw (84 km below power plant). Water samples were taken on ten cross-sections of Vistula course and on seven Vistula tributaries. In the vicinity of power plant the samples were taken at three points of the cross-section.
The investigations were performed once or twice a month.
Several times the water sampling was synchronized with the rate of the water flow.

The water quality of Vistula river upstream of the Kozienice power plant could be classified as average polluted shown by following parameters:

	Range
D.O mg/l O_2	9 - 14
BOD_5 mg/l O_2	0.7 - 10
Ammonia mg/l N	0.1 - 4.0
Nitrite mg/l N	0.001 - 0.09
Nitrate mg/l N	0.02 - 1.7

On the distance of 138 km between Pulawy and Warsaw, Vistula river water quality was changing due to the inflowing of waste and tributaries and selfpurification processes. Some changes of water quality were also observed in seasons. The largest difference was shown in ammonia concentration, from very low, 0.1 mg/l N in summer up to 4 mg/l in winter.
During the three years of study, a small improvement of the water quality was noticed.

An attempt was made to find, by the help of statistical methods, the relation between water quality parameter changes below the power plant and:

- water temperature
- water temperature increase
- ratio of thermal water discharge to river water flow.

The influence of thermal water discharge from the Kozienice power plant on water quality was small and shown mainly by a decrease of D.O concentration and an increase of nitrite concentration.

Special investigations were performed to determine the influence of thermal water discharge on the number and size distribution of suspended particles in Vistula water. The study was supported by laboratory experiments, when the influence of temperature changes in range 5-12°C was tested. For measuring the particles the conductive method was used with the help of Coulter Counter.

Laboratory investigations on the influence of temperature changes on biochemical processes rate for Vistula water have been performed. Temperature was changing between 4 and 40°C. From the obtained results the constant of biochemical reaction rate k_1, thermal coefficient θ, and coefficient of first stage of nitrification α_1 were calculated.

The formula for the determination of the permissible river water temperature from the point of view of oxygen criteria has been elaborated. The calculated temperature depends on water pollution with organics and parameters of selfpurification processes.

CONTENTS

Foreword V

Abstract VI

Figures. IX

Tables XII

Abbreviations and Symbols. XVI

Acknowledgment XIX

1. Conclusions. 1

2. Recommendations. 4

3. Present Investigations and Views about the Effect of Heating upon Quality of River Water. . . . 9

4. Characteristic of Study Object 12

   Area. 12

   Meteorological and hydrological conditions in the Vistula river basin between Puławy and Warsaw. 16

5. Hydrothermal Study 25

   Theoretical background of methods for evaluation of cooling process in rivers . . . 25

   Methodology 29

   Results 32

   Discussion. 36

      Thermal regime of Vistula water downstream of Kozienice power plant . . . 36

      Estimation of the models. 58

6. Hydrochemical Studies. 60

   Effects of the heated waters discharge on the Vistula water quality. 60

      Methods 60

      Results 64

      Discussion. 64

The changes of water quality along the Vistula river in the years 1973 to 1979 64

The effect of heated waters discharge from the Kozienice power plant on the Vistula water quality. 76

Mathematical model of water quality changes under the influence of thermal water discharge. 98

The effect of temperature on the size distribution of suspended particles in water 108

Introduction. 108

Materials and methods. 108

Procedure 112

Results 113

Discussion 114

The influence of temperature on the biochemical processes occuring in the Vistula river. 124

Materials and methodology. 124

Research results 125

Discussion 129

Determination of k_1 constant changes in various temperatures. 129

Determination of the rate of nitrification in different temperatures . . . 130

7. The Method for Permissible River Water Temperature Calculation Based on the Oxygen Criteria. 137

Critical oxygen deficit calculation 137

Formulation of oxygen criterion relation enabling permissible temperature calculation. 138

Examplary calculation of permissible temperature 153

References 158

FIGURES

Number		Page
1	Vistula river stretch under study	13
2	Locations of Vistula thermal investigations cross-sections downstream of Kozienice power plant	30
3	Variations of Vistula water temperature obtained from daily observations.	40
4	Vistula water surface temperature distribution downstream of Kozienice power plant. September 3, 1975.	54
5	Detention time nomograph on the Vistula stretch from km 371+700 to km 513+400 as a function of water level at Puławy gauge cross-section. . .	55
6	Location of sampling points on Vistula river and its tributaries	61
7	Changes of yearly water temperature along Vistula river	69
8	Changes of yearly of oxygen concentration along Vistula river	70
9	Changes of yearly BOD_5 along Vistula river.	72
10	Changes of yearly ammonia concentration along Vistula river	74
11	Changes of yearly nitrite concentration along Vistula river	75
12	Changes of yearly organic nitrogen concentration along Vistula river	77
13	Flows of Vistula river and capacity of Kozienice power plant in days water quality measurement . .	78
14	The differences of water temperature and D.O. concentration between station No.IV and No.3 (left bank)	83
15	The differences of water temperature and D.O. concentration between station No.4 and No.3 (left bank)	83

Number **Page**

16 Changes of D.O. concentration after water pass through cooling system, 1974. 84
17 Changes of D.O. concentration after water pass through cooling system, 1975. 84
18 Changes of BOD_5 after water pass through cooling system, 1973 86
19 Changes of BOD_5 after water pass through cooling system, 1974 86
20 Changes of ammonia concentration after water pass through cooling system, 1974. 87
21 Monthly changes of ammonia concentration of Vistula river around Kozienice 88
22 Changes of nitrites concentration after water pass through cooling system. 90
23 Changes of D.O. concentration in heated water channel and in Vistula water downstream of Kozienice power plant, April 15-16,1975. 93
24 Changes of Kozienice power plant capacity and increases of water temperature in April, 13-16, 1976. 93
25 Schematic diagram of Coulter Counter 109
26 Size distribution of particles suspended in Vistula water (9.1.1975) 119
27 Size distribution of particles suspended in Vistula water (10.22.1975) 119
28 Size distribution of particles suspended in Vistula water (11.11.1975) 120
29 Size distribution of particles suspended in Vistula water (12.2. 1975) 120
30 The influence of temperature on the distribution of particles suspelded in the water. 123
31 The influence of temperature on the distribution of particles suspended in the water. 123
32 Decrease of D.O. concentration in water in various temperatures, June 1974. 126
33 Changes of BOD_5 of Vistula water in various temperatures mean values from 5 measurements, 1974 126

Number **Page**

34 Decrease of ammonia concentration in water in various temperatures, April 1974 128

35 Changes of nitrite concentration in water in various temperatures, March 1974 128

36 The course of nitrification process of Vistula water in various temperatures, March 1974. The initial concentration of ammonia A=3,8 mg/l N. . . . 131

37 Dependence of coefficient α on temperature (α_t) for various temperatures calculated in percent of $\alpha_{(22,5^{\circ}C)}$ 131

38 Oxygen demand for nitrification of the I stage for Vistula water, March, 1974. The initial concentration of ammonia A=3,8 mg/l N 134

39 Oxygen sag curve in river water. 147

40 D.O. contents at critical point depending on temperature of Vistula river water below Kozienice power station, calculated for various pollutant levels 157

TABLES

Number		Page
1	The most important sources of waste water discharged directly into the Vistula river	14
2	The most important sources of waste water discharged into the Vistula tributaries	15
3	Comparison of monthly average air temperature values at some meteorological stations within Vistula basin between Puławy and Warsaw for period 1951 to 1970 with those in each year of period 1971 to 1979	17
4	Comparison of average of monthly max. and yearly max. air temperature values at some meteorological stations within Vistula basin between Puławy and Warsaw for period 1951 to 1970 with those in each year of period 1971 to 1979	18
5	Comparison of monthly average water temperature values of Vistula and its confluents for period 1951 to 1970 with those in each year of period 1971 to 1979	19
6	Comparison of monthly max. water temperature for May to September of period 1951 to 1970 with those in each year of period 1971 to 1979	20
7	Comparison of Vistula flowrates in each year of period 1971 to 1979 with characteristic data for period 1951 to 1970 at Puławy gauge	22
8	Comparison of Vistula flowrates in each year of period 1971 to 1979 with characteristic data for period 1951 to 1970 at Dęblin gauge	23
9	Comparison of Vistula flowrates in each year of period 1971 to 1979 with characteristic data for period 1951 to 1970 at Warsaw - Nadwilanówka gauge	24
10	Monthly max., average and min. generating capacity of Kozienice power plant in each year of period 1973 to 1979	33

Number		Page
11	Characteristic parameters of Kozienice power plant cooling system during expedition-type surveys	34
12	Characteristic parameters of cooling process during periodical surveys.	37
13	Monthly average and max. water temperature at three Vistula cross-sections	41
14	T_{av} and T_o temperature obtained by Energoprojekt's method for cross-section 1000 m downstream discharge	43
15	Comparison of T_{av} values evaluated by Jaworski's method with those calculated based on surveys results.	44
16	Comparison of T_{av} values evaluated by Edinger-Polk's method with those calculated based on surveys results	47
17	River water surface temperature interpreted from infrared pictures, September 3, 1975 4:20 a.m.	49
18	Critical periods for Kozienice power plant operation in each year of period 1973 to 1975. . .	57
19	Comparison of mean water temperature values in Vistula cross-section 1000 m downstream the discharge evaluated by Energoprojekt's, Jaworski's and Edinger-Polk's methods with those obtained from surveys results.	59
20	List of localisation of the sampling stations. . .	62
21	Averages of results Vistula river and its tributaries water quality measurement year 1973. . .	63
22	Averages of results Vistula river and its tributaries water quality measurement year 1974. . .	66
23	Averages of results Vistula river and its tributaries water quality measurement year 1975. . .	67
24	The capacity of power plant Kozienice (N), Vistula river flow above heated water discharge (Q) and in the discharge channel (Q_{zw}) during the time of water sampling - 1973	79

Number		Page
25	The capacity of power plant Kozienice (N), Vistula river flow above heated water discharge (Q) and in the discharge channel (Q_{zw}) during the time of water sampling - 1974	80
26	The capacity of power plant Kozienice (N), Vistula river flow above heated water discharge (Q) and in the discharge channel (Q_{zw}) during the time of water sampling - 1975	81
27	Frequency of negative and positive changes of water quality parameters upstream and downstream from the power plant stations No. 4 l - 3	91
28	Frequency of negative and positive changes of water quality parameters at the left and right river bank of the Vistula river (stations No. 4 l - 4 r)	92
29	The results of Vistula water investigation close Kozienice power plant during the critical periods	94
30	Range and average results of twenty-four hours investigation of Vistula river, April 15-16, 1975	96
31	Regression coefficients for model 2	105
32	Coefficients of variance	106
33	Temperature of Vistula water during the sampling	115
34	Changes of total number of suspended solid (5.2 - 33 μm) along the Vistula river	116
35	Changes of total number of suspended solid (5.2 - 33 μm) across the Vistula river	117
36	Changes of total number of suspended solid (5.2 - 33 μm) in Vistula water after passing through cooling system	118
37	Fifteen minutes test: average of total number of particles	121
38	Five hours test: total number of particles	122

Number Page

39 Changes of nitrite concentration in Vistula water, March 1974. The initial concentration of ammonia = 3.0 mg/l N 129
40 Results of nitrification process study 132
41 Oxygen deficit and critical moment values for Vistula river water at various temperatures 134
42 Permissible temperature T_d values, calculated for Vistula river water 139

ABBREVIATIONS AND SYMBOLS

This project involved three scientific disciplines: fluid dynamics (hydrothermal study), chemistry and biochemistry (hydrochemical study) and statistics (statistical evaluation). Some notations are duplicated between disciplines but with different definition.

HYDROTHERMAL STUDIES

B = river width (m)
B_o = heated water stream width (m)
C_p = of specific heat water (cal/g °C)
h = river depth (m)
h_{av} = average depth in river cross-section (m)
L = river stretch length (m)
Q = river rate of flow (m^3/s)
Q_s = heated water discharge (m^3/s)
T = water temperature (°C)
T_a = air temperature (°C)
T_o = average temperature of heated stream (°C)
T_{max} = max. water temperature in river cross-section (°C)
T_n = ambient water temperature (°C)
T_{av} = average water temperature in river cross-section (°C)
T_x = average water temperature in river cross-section x downstream of discharge (°C)
T_s = temperature of heated discharge (°C)
V = water velocity (m^3/s)
V_{max} = max. water in river cross-section (m^3/s)
V_{av} = average water velocity in river cross-section (m^3/s)
x = cross-section distance downstream of discharge (m)
y = distance from the bank at which the outlet is located (m)

y_{max} = distance of the profile at which T_{max} occurs from the bank at which the outlet is located (m)

β = coefficient determining dispersion of heated stream (Θ_s) into fresh one (Θ-Θ_s)

Θ = water temperature increase above ambient river water temperature (°C)

Θ_o = water temperature increase in heated stream (°C)

Θ_{max} = max. water temperature increase in river cross-section (°C)

Θ_p = initial water temperature increase (°C)

Θ_{av} = average water temperature increase in river cross-section (°C)

MATHEMATICAL MODEL OF WATER QUALITY CHANGES UNDER THE INFLUENCE OF THERMAL WATER DISCHARGE

ΔC_i = concentration difference of the i-th substance between the areas upstream and downstream from the power plant

δC_i = the i-th concentration difference between the left and the right bank of the river downstream from the power plant

y_i = value calculated from formulas 19 and 20

Q = the flow rate in the vicinity of the power plant

q = heated waters discharge

ΔT_i = an increase in water temperature downstream from the power plant

T_j = water temperature upstream the power plant

$\bar{C}_{ji}$ = average concentration value of the i-th substance upstream from the power plant

NPOM = a number of measurements in a sample

A,B = regression coefficients

ρ_{ij} = coefficient of partial correlation

W = matrix of variance-covariance

M_{ij} = minor value of the matrix

b_i = coefficients of regression

μ_i = mean value

N = capacity of the power plant

V_i = variance coefficients

σ_i = average deviation

$d_{(xi)}$ = average deviation (dispersion)

C_{iL} = concentration of the i-th substance at the left river bank below the power plant

C_{ir} = concentration of the i-th substance at the right river bank above the power plant

HYDROCHEMICAL STUDY

k_1 = BOD rate constant using log base 10, d^{-1}

k_2 = reaeration rate constant using log base 10, d^{-1}

L_0 = initial BOD as ultimate first stage BOD, mg/l O_2

L_t = BOD remaining at time t, mg/l

L_1 = hypothetical BOD, calculated following equation 21 section 7, mg/l

Θ_1 = thermal coefficient of k_1

Θ_2 = thermal coefficient of k_2

t_{cr} = critical time at which the maximum oxygen deficit is reached, days

D = oxygen deficit at time t, mg/l O_2

D_0 = initial oxygen deficit, mg/l O_2

C = dissolved oxygen concentration at critical point, mg/l O_2

f = selfpurification coefficient

f_0 = selfpurification coefficient at 20 °C

T_d = maximum permissible temperature, °C

α_1 = first stage nitrification rate coefficient, d^{-1}

NOD = oxygen demand for nitrification, mg/l O_2

t_1 = half-life time of reaction for nitrification process, d

A_1 = initial ammonia concentration, mg/l as N.

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Technical contribution to these studies were made by all staff of Department of Water Chemistry and Biology and Department of Hydrophysics of IMWM. Their assistance is sincerely appreciated.

SECTION 1

CONCLUSIONS

During the period of research 1973 - 1975 extreme conditions did not occur i.e. maximal ambient water temperature, low flows, and full capacity of the power plant.
Therefore, the power plant effect on the natural thermal regime was not large. The results show as follows:

- The hydraulic system of the discharge and relatively small depths in the river range 1.5 - 2.0 m caused the lateral stratification and uniform vertical distribution of temperature.
- The zone of intensive mixing process was estimated on the 1000 m of length at normal plant operation.
- The length of the stretch under the heated waters influence was estimated as equal to 50 km.
- The maximal observed temperature difference between the thermal water discharge and water above the power plant was 23.9 °C (November, 29.1974).
- The maximal difference between the average water temperature in the river cross-section 1000 m downstream of the discharge and the water temperature above the power plant was 5.5 °C (April, 5.1975).
- The maximal difference between the water temperature of left and right bank of the river in the cross-section of 1000 m below the power plant was 9.2 °C (April, 5.1975).
- The maximal value of the temperature observed in the cross-section 1000 m downstream of the discharge was equal 26.8 °C (August, 11.1975).
- The agreement between the computed and measured mean temperatures was relatively satisfactory. Therefore all the three methods can be accepted for the calculation of the mean temperature distribution along the river course. Computed average values of the temperature were satisfactory in comparison with the measured ones, however the computed temperature distributions in the cross-section were not satisfactory as compared to measured values.

Studies on the effects of heated waters from the Kozienice power plant on the Vistula water quality were performed at the variable degree of river water heating. The differences between water temperature upstream and downstream of thermal water discharge was from 0 to 6,0 °C. At such values of water temperature increase it was noticed:

- Dissolved oxygen concentration decrease, reaching 2,4 mg/l O_2. The D.O. concentration changes did not correlate with the value of water temperature increase. It was noticed, that the higher the concentration in inflowing water, the larger its decrease.
- Increase of nitrite concentration to 0,020 mg/l N .
- In some cases the tendency of decreasing of BOD_5 and ammonia concentration was observed in stream of heated water, but only at high values of those parameters.
- Other water quality parameters did not change in a visible way.
- Influence of thermal water discharge from the power plant on the quality of Vistula river was limited to a few kilometers below the discharge of thermal water.
- In laboratory investigations the influence of temperature changes on the rate of organic compounds biodecomposition in Vistula water was determined. Calculated $k_{1\ 20°C}$ - constant of biochemical reaction rate for Vistula water in the vicinity of Kozienice was 0,1 d^{-1}, and thermal coefficient θ was 1,024.
- The influence of temperature changes on nitrification rate was stated. The maximal nitrification rate was observed at the temperature of about 20 °C. The coefficient characterized the rate of the first stage of nitrification the oxidation of ammonia into nitrites α_1, showed values between 0,15 and 0,68 d^{-1}, depending on water quality and incubation of temperature. The mean value $\alpha_{1\ 20°C}$ was 0,3 d^{-1}.
- Statistically calculated relations between water quality changes and: a) water temperature, b) water temperature increase and c) ratio of thermal water discharge to river flows, were very poor.

  A small relation was observed only for Dissolved Oxygen concentration, nitrites concentration and BOD_5.
- The number and size distribution of suspended particles in Vistula water diameter 3.3 to 33 microns did not change visibly under the influence of the thermal water discharge from the Kozienice power plant.
- In the case of high water pollution with easily degradable organics, the increase of water temperature may cause critical oxygen deficit. The maximal, permissible temperature from the point of view of oxygen balance can be calculated from the fol-

lowing formulas created in the project:

$$T_d = \frac{11,749 - C - \dfrac{0,79L_1(1+f_0+30\alpha f_0)}{(1+f_0)^2}}{0,137 - \dfrac{0,79L_1\alpha f_0}{(1+f_0)^2}}$$

for $0,9 \leq f_0 \leq 2,9$

or

$$T_d = \frac{11,749 - C - \dfrac{0,889L_1(1,997+f_0+30\alpha f_0)}{(1,997+f_0)^2}}{0,137 - \dfrac{0,889L_1\alpha f_0}{(1,997+f_0)^2}}$$

for $2,9 < f_0 < 10$

- Using that formula it was calculatud that for Vistula water in the vicinity of Kozienice a critical oxygen deficit will not occur when the organic pollution of water will be below BOD_5 = 10 mg/l (actual BOD_5 of Vistula water in Kozienice is in the range 1 - 10 mg/l O_2). The negative influence on the oxygen balance could be expected at a higher organic pollution of the river.
- When the concentratior of ammonia is high (few mg/l as N) the raise of temperature may increase the rate of nitrification and influence substantially the oxygen consumption rate, but only in the temperature range between 10 and 20°C i.e. in spring and fall time.

SECTION 2

RECOMMENDATIONS

The field investigations of the influence of thermal water discharge from the power plant on the thermal conditions and the quality of receiver water are very useful for determining the permissible water temperature for the tested river and for other rivers.

The future research works on the influence of the thermal water increase on water quality should be limited for evaluation of oxygen balance and nitrification process.

For the water highly polluted by easily degradable organic compounds, the permissible water temperature from the oxygen balance point of view, could be calculated from the formula suggested in this paper.

A discreet model should be prepared to have more accurate solutions of temperature distribution in mixing zone along the river course, because the agreement between computed and measurement temperature distributions was not satisfactory.

SECTION 3

PRESENT INVESTIGATIONS AND VIEWS ABOUT THE EFFECT OF HEATING UPON QUALITY OF RIVER WATER

Until now there have been few investigations on the effect of heating upon the biochemical processes and chemical composition of waters. On the basis or the present investigations in laboratories and on the rivers, it is a general view that the heating of water causes the following changes:

- decrease of oxygen solubility,
- accelerated decomposition of organic substances and on increase of oxygen usage,
- acceleration of the nitrification process,
- accelerated oxygen usage by water organisms (mainly during the night) ,
- increase of corrosion,
- increase of algae production which, after decay, might cause secondary river pollution,
- increase of toxicity of heavy metals, pesticides and other contaminants (harmful substances),
- decrease of ice cover and the period of its duration and different aeration conditions connected with it,
- decrease of receiver's assimilating capacity.

The above mentioned phenomena, have in principle a negative effect on the quality of water; here also lies the source of fear of excessive thermal water pollution. Investigations on the influence of heated water discharge on the water chemistry of a receiver gave different results, though that depended upon the amount of heating and river pollution above the power plant.

Some results of those investigations and, consequently, the views of the researchers on the matter of thermal pollution are presented below.

Krenkel (1)discovered the influence of heating on the receiver's capacity for the assimilation of sewage negative. He carried out his research on the Coosa River, into which the waste discharged in the amount of 13 tons BOD per 24 hours did not cause negative effects on the oxygen conditions at river temperature of 25°C. When water temperature increased to 30°C the same pollution load resulted in the decrease of oxygen concentration below 4 mg/l O_2, which is lower than the permissible value for that river. Krenkel calculated that in order to maintain oxygen conditions at the previous level, it is permissible to discharge only 5 tons of BOD per 24 hours into the river; it means that the increase of water temperature by 5°C was equivalent to the waste load of 8 thousand tons of BOD per 24 hours.

Suszczewski (2) stated that a discharge of heated water improves oxygen conditions in winter time, preventing a river from being covered with ice in certain sections below a power plant.

Stangenberg (3,4) brought attention to different effects that a discharge of heated water has on a river: either harmful indifferent or useful. He took as an example the excessive heating of the Nysa Łużycka River (in summer up to 36°C, in winter up to 6.5°C), by the discharge of water from the Hirschfelde power plant (270 MW of power capacity) causing changes in the water chemistry and its biocenosis. The increase of water temperature caused a decrease of oxygen concentration down to 3,8 mg/l O_2. At the same, Stangenberg took into consideration the hypothetical situation of heating of the Odra River waters within the section from the country border to Wrocław. Organic matter, mainly phenols, would have undergone faster biochemical decomposition and the quality of waters upstream of Wrocław would have been improved. It would have been a positive effect of a discharge of heated waters.

Gustafson (5) analyzed the influence of a discharge of heated waters from three nuclear power plants: Point Beach, Donald C.Cook and Zion on Michigan Lake. He found that there is no harmful influence upon the quality of water. Simultaneously, he made a statement that thermal pollution is being treated in an exaggerated way nowadays, similarly to the pollution by radioactive substances; whether there are any changes in the environment or not, the discharge of heat is considered as a dangerous. He stated also that the heat provided into water body is always the same - independently of whether it is natural heat or a discharge of heated water. The effect that the increase of temperature has upon the water environment is always the same, irrespectively of the source of heat.

Investigations of on influence of a discharge of heated water from the Martins Creek power plant on the Delaware River, carried out in 1956 (6) showed that the changes in chemical constitution were small. Only small decrease of oxygen concentration in the water below the power plant was observed.

Foerster (7) carried out four-years investigations on the influence of heated water discharged from nuclear power plant in East Haddam (590 MW of power capacity) upon the quality of receiver waters. Five and one half percent of the river flow was used for cooling purposes, and the water temperature, after the water passed through a cooling system, increased by 7,1 °C however the heated water was discharged into the river by a channel of 1,8 km of length. Foester found small changes in the quality of the receiver water; a small decrease of pH, dissolved oxygen and nitrogen concentration while there was a distinct increase of nitrite concentration (from 0.23 up to 0.31 mg/l).

Investigations carried out by the University of North Carolina in USA (8) on a discharge of heated water on the water chemistry did not show any correlation between an increase of temperature and calcium, phosphates and nitrates concentrations.

Engle (9) and Ward (10) showed in their investigations that a discharge of heated water from a power plant does not cause any change in pH values and water alkalinity.

Beer (11) found, that in the Michigan Lake, in the place where water is being heated by power plants, concentrations of ammonia smaller than in the rest of the lake appeared.

Investigations on the influence of heated water discharge from the Konakow power plant on the quality of the Iwanowski Impoundment situated on the Upper Volga have been accomplished (12). Water temperature below the power plant increased in winter by 11,3 °C and in summer by 9,7 °C, and the maximum temperature observed was 31,4 °C. It was observed that in the area where heated water mixes with the water of a receiver, in winter time the dissolved oxygen concentration increases.

Driver (13) found a big dependence of oxygen deficit in a river upon the water temperature. For practical purposes he formulated an empirical formula for calculation of oxygen deficit in the river below a source of waste in order to evaluate assimilatory capacity of the Coosa River.

$$D = \frac{37,03 \cdot Q^{0,01}}{a^{0,1} \cdot q^{0,51}}$$

where: D = oxygen concentration, mg/l O_2

Q = water - flow in a river,

L = BOD_5 of discharged waste pounds/24 hours

T = temperature in °C

Oxygen concentration in river water is dependent on river flow, discharge of waste and temperature. The formula shows that DO concentration decreases with an increase of temperature, and that water temperature influences oxygen concentration much more than flow or discharge of sewage.

An increase of temperature enlarges the toxicity of many substances polluting water towards water organisms. The results of laboratory investigations carried out by Schaeffer (14) proved this statement. Schaeffer investigated the toxicity of chromium compounds towards *Rotatoria Philodina roseola* obtaining an increase of toxicity with an increase of temperature.

Temp. °C	5	15	20	25	30	35
TL_m, mg/l as Cr	65	43	37	28	23	18

Urban (15) states that heating of waters increases the toxicity of metals and pesticides in water environment.

Laberge (16) found that an increase of temperature by 10 °C doubles the potassium cyanide toxicity towards fish.

Chirac (17) investigated the influence of a discharge of heated water from a power plant upon the River Jiu in Rumania. When 28 % of river flow was used for cooling, the temperature of the receiver water increased by 3.2 °C, reaching 25.5 °C. Oxygen concentration at 0.6 km below the discharge point decreased by 0.5 mg/l, whereas oxygen saturation stayed at the same level of 94 %. At a distance of 6 km below power plant the difference in oxygen concentration between water at this point and the inflow of water was 1 mg/l, while oxygen saturation decreased by 10 %. When 78 % of river flow was used for cooling, water temperature in a water receiver increased by 21 °C, reaching a high value of 39.5 °C. Oxygen concentration of in flow water, which was 128 % of saturation decreased by 30 % (i.e. by 4.8 mg/l O_2). Inflow water was very clean; BOD_5 ranged from 1.5 to 2.2 mg/l O_2. Heating of water did not effect BOD_5 in a visible way.

In certain cases the influence of heated water has a positive effect.

The quality of polluted waters of the Regnitz River in West Germany (18) improved a lot after the discharge of heated waters from the Franken II power plant, which uses 80 % of the river flow. Oxygen concentration increased from 0 up to 7 mg/l O_2 and BOD_5 quickly decreased from 23 down to 12 mg/l O_2.

Investigations on the Rhine River (19) proved that an increase of water temperature causes an increase of water corrosion towards water contructions particularly when chloride concentration is high.

Appourchaux (20) carried out a two-year investigation on the influence of the Monterau power plant 250 MW of power capacity on the waters of the Seine River.

The use of water for cooling was 10 m^3/s with the river flow of about 30 m^3/s. The difference between temperatures of intake water and water discharged was 6 to 7 °C; 6 km below the discharge of water, an increase of temperature by 1 - 2 °C appeared. The investigations showed no changes either in the concentration of dissolved oxygen in water or in dissolved matters concentration.

Ross (21) from the Central Electricity Generating Board, U.K., presented a statement that the heating of water has no negative effect upon the quality of waters. He found that water loses oxygen after heating only if it is in 100 % saturated with oxygen. Yet most of the rivers in England carry water with oxygen concentration close to a 100 % saturation. Besides, if there is a lot of oxygen in water, a decrease of oxygen concentration appears only when super saturation appears. Then the loss of D.O will be small, anyhow. Nevertheless, if the water with low oxygen concentration is used for cooling, aeration at discharge may result in an increase of oxygen concentration. Additionally, Ross suggested that the danger of reaching a high deficit of oxygen caused by heating and acceleration of biochemical processes is small for slightly polluted rivers. This danger may appear when waters are heavily polluted with organic matter.

Investigations were conducted on the effect of water discharge from the Skawina power plant upon the Skawinka and Vistula Rivers. The Skawina power plant (550 MW of power capacity) is situated at 3.3 km of the Skawinka River, the right tributary of the Vistula River (km 60 + 500). The flow of the Skawinka River in this place is 3.6 m^3/s. Due to such small water flow, the water for cooling is taken from the Vistula at Łączany (at 38th km) and is supplied for the power plant through the Łączany - Skawina channel, which is 17 km long. The power plant consumes from 16 to 24 m^3/s of water for cooling purposes. Heated waters are discharged to the Skawinka River, which at 3.3 km joins the Vistula. The average low flow of the Vistula River below the Skawinka River is 23.4 m^3/s, so the water consumption of the power plant varies from 68 to 102 % of the Vistula River flow, at its low water level.

Investigations carried out during the period 1962 - 63 gave following results (22). Increase of water temperature after flowing through condensers amounted to average 7 °C and maximum 9°C The maximum temperature of the water discharged from a power plant observed in July, 1963 was 35°C. The highest water temperature in the river (that is 34 °C) was marked also in July, 1963; at the same time the natural temperature above the power plant were also high.

Oxygen concentration of water passing through condensers underwent certain changes, sometimes increased by 0.7 - 2.1 mg/l; in other periods it would decrease to 1.8 mg/l O_2. There were also periods when oxygen concentration did not change. Yet, there was a systematic decrease of oxygen concentration in the Vistula River below the power plant, sometimes even by 3 mg/l O_2

The smallest dissolved oxygen concentration in this section of the Vistula River amounted to 2 mg/l O_2. There was also a decrease in the percentage of oxygen saturation.

The Vistula waters at the point of heated waters discharge were rather highly polluted. Above the power plant BOD_5 ranged from 3.1 to 15.2 mg/l O_2 and COD from 12 to 29.4 mg/l O_2. In the cross-section below the power plant BOD_5 varied from 2.5 to 16.4 mg/l O_2 and COD from 10.0 to 33.4 mg/l O_2. Such small changes did not allow for drawing conclusions about the direction of changes in water quality caused by heating. Other parameters of chemical water pollution such as chlorides, phosphates, pH, suspended solids, nitrogen compounds and phenols did not undergo any serious changes under the influence of heating.

Investigations carried out in 1968 and 1969 (23) showed similar results. At the conclusion of investigation it was stated that the discharge of heated water from the Skawina power plant did not cause any essential changes in the chemistry of the Vistula waters.

Investigations were conducted on the effect the discharge of heated waters from the power plant in Ostrołęka upon the waters of the Narew River (24). There are two power plants in Ostrołęka: power plant A with a power capacity of 80 MW, and power plant B with a power capacity of 600 MW. They work by an open cooling system. Ostrołęka B power plant was set opened in 1972 and it requires 25 m^3 of water per second. Investigations of the influence of heated waters on the quality of the Narew River waters were carried out in 1972 and 1973. In 1973 the average power out put of the power plant was 313 MW, and at maximum it was 345 MW. When the flow of the Narew River amounted from 41 to 215 m^3/s, the water consumption for cooling purposes of the power plant equalled from 8 to 37 % of river-flow.

The temperature of water in the cooling circuit of the power plant increased on the average by 8.7 °C. The largest difference between the temperatures of heated waters discharged from the power plant and the waters of the Narew River was 21 °C. Just below the discharge of heated waters the temperature of the Narew River waters increased maximally by 8 °C. The temperature of the river water decreased quickly and at 1.5 km below the power plant the increase of temperature did not exceed 2 °C.

The passing of water through a cooling system of turbine sets of the power plant caused small decrease of oxygen concentration; in extremes only by 2.2 mg/l O_2. Yet, at the same time the increase of temperature increased the percentage of oxygen saturation.

Heating of water very often caused minor decrease of BOD_5, although there also appeared instances of small increase of BOD_5.

In the thermal water as well as in the river water below the power plant a clear increase of nitrite concentration was observed. Other determined compounds of water like nitrates, phosphates, turbidity colour, pH, odor and dry residue did not undergo any essential changes.

Generally speaking, the discharge of heated water from the Ostrolęka power plant caused small changes in the chemical composition of water and it did not cause the deterioration of its quality.

SECTION 4

CHARACTERISTIC OF STUDY OBJECT

AREA

The area of the Vistula River catchment along the stretch between Puławy and Warsaw is equal to 27609 km^2, which means 33% of the total basin from the source to Warsaw (Fig. 1). The part of the catchment mentioned above is situated in three natural regions: Małopolska Highland, Lubelska Highland and Mazowiecko-Podolska Lowland. Highland Krakowsko-Częstochowski, Świętokrzyskie Mountains and Roztocze - Country.

The main part of the area has small differences in elevation. Higher hills, more than 300 m above the sea level are only in the high Pilica and Wieprz basins. The elevation lower than 200 m a.s

Some larger left-bank confluences are: Zagożdżonka, Radomka, Pilica, Czarna, Jeziorka, and right bank: Kurówka, Wieprz, Okrzejka, Wilga, Świder.

The Vistula river within the section between Puławy and Warsaw at the distance from 372th km to 509th km is exploited as a source of water supply for both the communal and industrial purposes and it is also used as a receiver of waste water from the plants situated in its drainage area. The most important uses are: the intake of drinking water for the City of Warsaw (at 509.8 km) and the intake of water for industrial purpose by the power plants of Siekierki (504.6 km) and Kozienice (426.0 km) and also by the Nitrogen Plant in Puławy.

The most important sources of waste discharged directly into the Vistula River and indirectly through its tributaries are presented in tables 1 and 2.

Intensive exploitation of the Vistula River as a receiver of waste from towns and industrial centers situated along the river between Puławy and Warsaw, has a big influence on the quality of the Vistula River waters. Taking into consideration a permissible pollution standard, the waters of the Vistula River are of no use for any economic purposes at about 30 % of its all length.

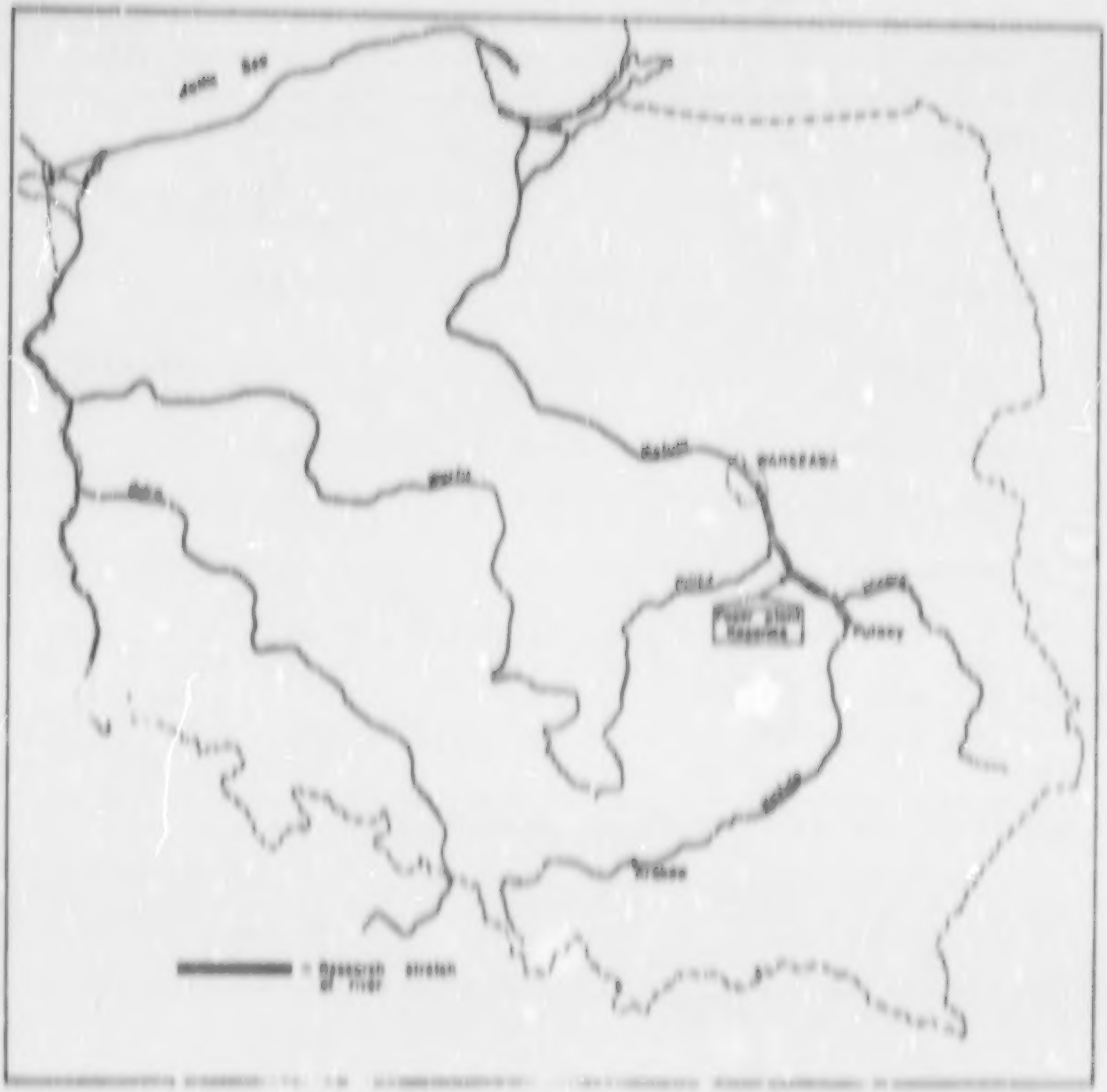
Baltic Sea
WARSZAWA
Pulawy
Krakow
= Research stretch of river

Fig. 4. Vistula River Stretch under Study

Table 1. The most important sources of waste water discharged directly into the Vistula River

Places	km of the River	Kind of waste water
Puławy	371.5	municipal
	376.1	municipal and industrial (from the Nitrogen Plant)
Dęblin	392.5	municipal
	393.4	
Kozienice	426.5	industrial (thermal water)
Góra Kalwaria	476.0	municipal
Warsaw-Siekierki	504.6	industrial (thermal water)

The Kozienice power plant is situated at 55th km downstream of Puławy on the left bank of the Vistula (at the 429th km from the source).

The first 200 MW unit was put into operation in November 1972. 4 units were constructed in 1973 and 2 units in 1974. The construction was finished in February 1975 and then the power plant reached the designed capacity of 1600 MW.

The station operates with a once - through cooling system. The intake is located 0.7 km upstream of the outlet. Both, the intake and the outlet are open channels. The condenser of one unit needs 8,35 m^3/s of water, which is heated by 7.5 °C. In other words the Plant requires 66,8 m^3/s to operate with the full capacity of 1600 MW.

Table 2. The most important sources of waste water discharged into the Vistula tributaries

Places	Tributaries	km of Vistula river	Kind of waste water
Kępice	Wieprza	391.7	industrial
Sławno			municipal
Darłowo			municipal
Pionki	Zagożdżonka	424.7	municipal industrial
Kozienice City			municipal
Radom	Radomka	431.2	municipal
Garwolin	Wilga	490.1	municipal industrial
Żelechów	Wilga		municipal industrial
Warka	Pilica	462.5	municipal
Karczew	Świder	490.0	municipal
Otwock	"	490.0	"
Józefów	"	490.0	"
Świerk	"	490.0	radioactive
Piaseczno	Jeziorka	493.7	municipal
	"	493.7	industrial
Konstancin	"	493.7	municipal industrial
Tarczyn	"	493.7	municipal industrial
Grójec	"	493.7	municipal

METEOROGICAL AND HYDROLOGICAL CONDITIONS IN THE VISTULA RIVER BASIN BETWEEN PULAWY AND WARSAW

Air Temperature

The air temperature data collected at Puławy, Radom and Żelechów meteorological stations are given in table 3,4. There are average and maximum values from the period 1951-1970 compared with the corresponding ones from 1971-1975. It can be seen that the monthly, semiannual and annual averages for both periods are close to each other. The averages from the winter semiannuals, of the 1971-1975, are however much higher than the values from the period of 1951 to 1970. The averages from the summer semiannuals of the 1971-1975 period are similar to the values from 1951 to 1970. The max. values observed in 1971-1975 were lower than max. values observed during the 20-year period. In other words, the max. values observed during the months critical for cooling process were not much higher than the average values observed during 1951-1970.

Water Temperature

The average monthly values observed at 7 a.m. at the profiles: Puławy, Królewski Las and Warsaw of the Vistula River are given in table 5. There are also the values for the Kośmin profile of the Wieprz River and Białobrzegi of the Pilica River. The periods of observation are: 1951 - 1970 and 1971 - 1975. The satisfactory agreement between long term average temperature and average temperature for the period 1971 - 1975 can be seen from the table. A small water temperature rise (1°C) above the long term average was observed in 1975.

The max. temperature observed during summer months of the period 1971 - 1975 was lower than that observed during the 20-year period by about 3°C (Table 6).

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Name of stations	Year or period	Months												Winter	Summer	Year
		XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI–IV	V–X	XI–X
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
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Table 5. Comparison of monthly max.and average of mon. water temperature for May to September of period 1951-1970 with those in each year of period 1971-1975

River gauge	Year or period	V	VI	VII	VIII	IX
1	2	3	4	5	6	7
Vistula-Puławy	av. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1971	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1972	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1973	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1974	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1975	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vistula-[illegible]	av. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1971	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1972	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1973	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1974	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1975	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vistula-Warsaw	av. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1971	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1972	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1973	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1974	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1975	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Wieprz-Kośmin	av. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1971	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1972	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1973	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1974	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1975	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pilica-Białobrzegi	av. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1951 - 1970	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max. 1971	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1972	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1973	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1974	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	1975	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The Typical Rates of Flow in the Vistula River

The typical rates of flow for: monthly semiannual and annual intervals are given in tables 7,8 and 9. These tables were elaborated for the 20 years period from 1951 to 1970 and the period of 1971 to 1975. The data were collected in 3 gauges installed at Vistula (e.i. Pulawy, Dęblin and Warsaw).

The symbols for the flowrates are as follows:

- SWQ - the annual maximum mean daily flow for the period of observation,
- WQ - the highest flow in: year, halfyear, month
- SSQ - the average annual flow for the period of observation,
- SQ - the average flow in: year, halfyear, month
- SNQ - the annual minimum mean daily flow for the period of observations,
- NQ - the lowest flow in: year, halfyear, month.

In the period of duration of the project the flows were observed as follows:

1973 - The annual average flow was lower than the long term average; at Warsaw the values were equal to 499 and 580 m³/s, respectively. The difference was caused by low flows in the months: 11 to 2 and 9 - 10. During summer months 6 - 8 the average value was similar to the average from the long term period.

1974 - Annual average flowrate at the Warsaw cross-section was higher than SSQ 96 m³/s whereas semiannual summer average flow was higher by 479 m³/s. During summer months low flows were also far higher than SNQ. However, during winter the halfyear flows were lower than the long term average.

1975 - The annual average flow at Warsaw was higher than SSQ 241 m³/s. The average flows for several months were also higher than long term average values. Low flows were not observed close to SNQ during the whole year.

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[illegible]	[illegible]												[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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SECTION [illegible]

HYDROTHERMAL STUDY

THEORETICAL BACKGROUND OF METHODS FOR EVALUATION OF COOLING PROCESS IN RIVERS

The applied models can be classified as follows (25):

1. based on the total energy budget;
2. based on the additional heat budget;
3. based on the assumption of an exponential-type decrease of water temperature up to the equilibrium temperature value and evaluation of the heat exchange coefficient from the heat budget;
4. based on the same assumption and evaluation of the heat exchange coefficient from the empirical formulas;
5. based on the empirical relationships, where hydrological and meteorological parameters determined from the statistical calculation are included.

In order to test the applicability of the methods for the evaluation of the cooling process in Polish rivers the results of computation by some of them were compared with calculated data.

The following methods were tested:

- elaborated by "Energoproject" Desing Office belonging to the 1-st group;
- Edinger-Polk's belonging to the 4-th group;
- Jaworski's belonging to the 5-th group.

Energoproject method (26)

This method is based on the total energy budget. Water temperature in the rivers downstream of the heated water's discharge is computed on the basis of the quantitative heat balance equation. The following conditions are assumed:

1. The cross-section for which computations are done is located

relatively close to the discharge and therefore heat losses into the atmosphere can be neglected.

2. Mean temperature in heated stream is higher than mean temperature in cross-section.
3. The heated water discharge is lower than the rate of flow.
4. The interface between the heated and fresh water is the isotherm with fresh water temperature.

The following relationships were formulated in order to calculate the average temperature in the heated stream:

$$T_C = \frac{(Q - Q_s)\cdot\beta\cdot T_N + Q_s(T_N + \theta_p)}{(Q - Q_s)\beta + Q_s}$$

and the average temperature in the cross-section of the river:

$$T_{av} = T_N + \beta(T_C - T_N)$$

Coefficient determines the composition phase of the heated stream (Q_s) and fresh one $(Q_N = Q_s)$; $(\beta < 1)$.

Values of the coefficient can be taken from the "Energoproject" report, where the graph of the function is included:

$$\beta = \varphi\left(\frac{Q_s}{Q};\ \frac{x}{B}\right)$$

Jaworski's method

Jaworski prepared his method on the basis of the investigation carried out in the Nowa Huta vicinity on the impounded section of the Vistula affected by the heated water discharge (27). He prepared the empirical model for determining the mean temperature in a cross-section with the accuracy of 0.3 °C. The input data are taken from the standard hydrological and meteorological network observations. Because the model which was tested different conditions - Narew River, Ostrołęka vicinity; San River downstream Stalowa Wola; and undefined river in USA - gave satisfactory results according to the author's statement, it was also checked for the stretch of Vistula River downstream of the Kozienice power plant.

The formula describing the average temperature in the cross-section at the distance x is following:

$$T_{av} = T_{mix} + k_x - \left[0{,}0437 \left(\frac{10 \cdot (x-70) Q_s}{Q \cdot V_{av} \cdot \theta} \right)^{0{,}359} - 0{,}1 \right]$$

where: $k_x = 0{,}0024 \cdot Q_s T_s \rho_w C_s - 0{,}26$

$$\theta = \frac{\Theta_n}{B} \; 11{,}4 - 0{,}16 \, T_n$$

$$T_{mix} = \varphi T_s + (1-\varphi) T_n = \theta_p + T_n$$

$$\varphi = \frac{Q_s}{Q}$$

The term k_x describing the uncontrolled underground flux of heat from the discharge channel is negligible in the Kozienice case because there exists only the short concrete channel.

Edinger - Polk's method (28)

Most of rivers in Poland are free-flowing. Therefore assumed one dimensional model with uniform temperature distribution in cross-sections, beginning from the source, gives poor information about the real distribution in the river, for the reason that the mixing process is not included in it.

The effect of the mixing process is, however, included in the Edinger-Polk method. This method is based on the three - dimensional energy conservation equation.

$$\frac{\partial s}{t} + u \frac{\partial s}{x} + v \frac{\partial s}{y} + w \frac{\partial s}{z} = \frac{\partial s}{C_w} + \frac{\partial}{x} \left(D_x \frac{\partial s}{x} \right) +$$

$$+ \frac{\partial}{\partial y} \left(D_y \frac{\partial s}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial s}{\partial z} \right)$$

After reduction to a one-dimensional form, with the assumption of a steady state condition of the flow, one may obtain the following solution:

$$T_i = T_N + \Theta_p \cdot \exp\left(-\frac{k \cdot x_i}{\varrho \cdot c_p \cdot v \cdot h}\right)$$

For steady - state condition the equation may be reduced to the two-dimensional form:

$$u \frac{\partial T}{\partial x} = \frac{\partial}{\partial y}\left(D_y \frac{\partial T}{\partial y}\right) - \frac{K}{\varrho h c_p} \Theta$$

where three mechanisms are included: advection, dispersion and heat exchange. If one assumes that D_y = const the equation has a solution:

$$T_{x,y} = T_N + \Theta_p \cdot 2\left(\frac{\xi_0}{\xi}\right)^{1/2} \cdot \exp\left(-\frac{y^2}{4\xi}\right) \cdot$$

$$\cdot \exp\left[-\alpha\left(\xi - \xi_0\right)\right]$$

$$\alpha = \frac{K}{\varrho c_p v h}$$

$$\xi = \frac{x \cdot D_y}{u}$$

$$\xi_0 = \frac{B^2}{\pi}\left(\frac{u h}{q}\right)^2$$

The reflection from the discharge side bank is taken into consideration.

The temperature distributions after one- and two-dimensional models were computed for that report.

Least square optimization were applied to evaluate the magnitude of the heat exchange coefficient:

$$\sum_{i=1}^{n} \left(\theta_i - \theta_p \exp\left[- \frac{K_x}{c_p v\ h} \right] \right)^2 \Longrightarrow \min$$

The obtained values were used to determine the theorutical temperature distributions according to the above relations.

METHODOLOGY

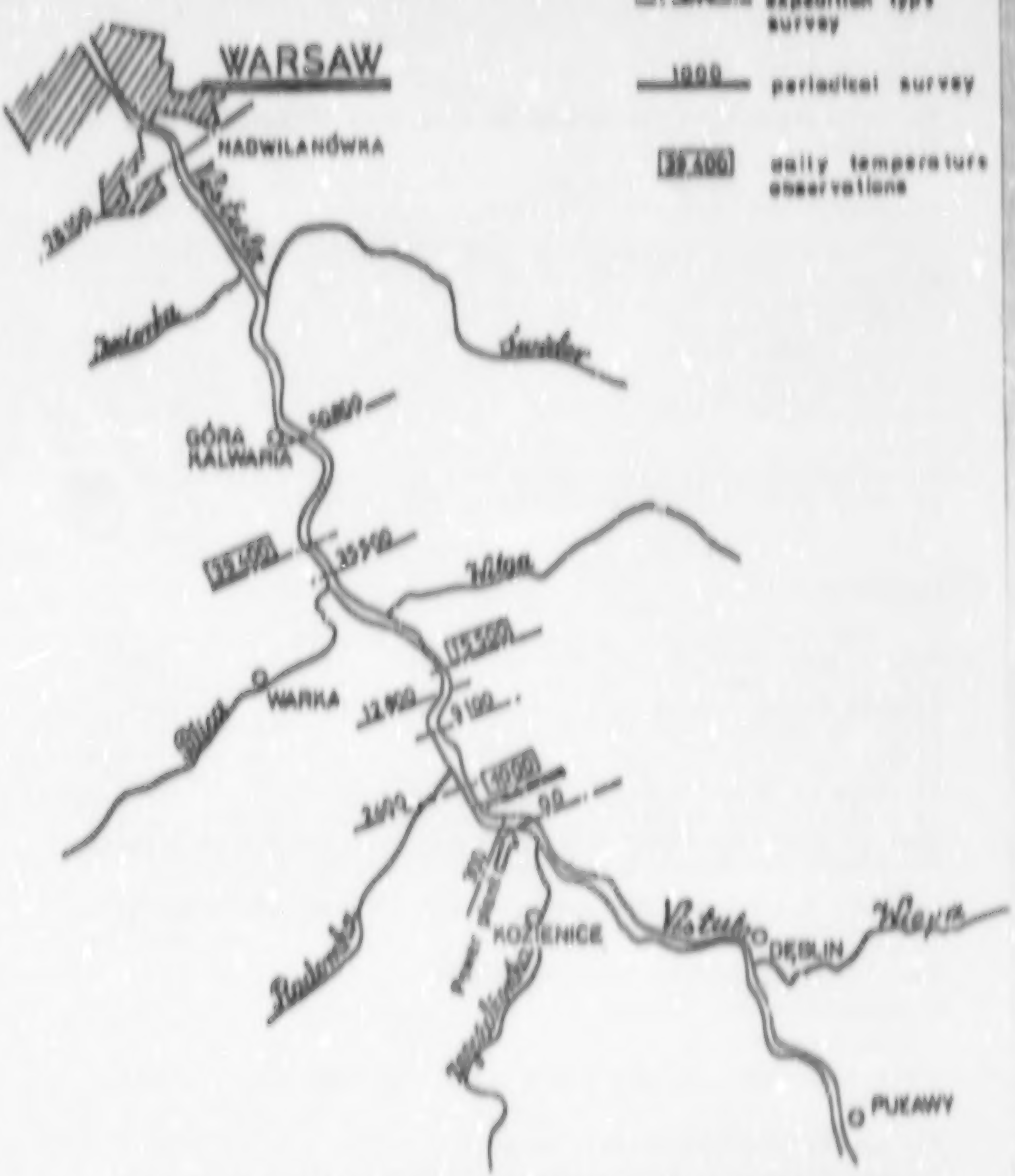
The detention time graph had to be prepared to carry out the thermal chemical and biological study properly. The graph was used to determine the exact moment of taking samples and temperature measurements at several rates of flow. The tracer study was carried out to evaluate the existing velocity of the plume. That was done for the section between Puławy and Warsaw in 1971 to 1973. The standard data collected by the Institute in gauge profiles were also used in the elaboration of the graph. As a result, the function between velocity of tracer plume and rate of flow were formulated and then the time of flow between the source and sampling profiles was obtained.

The temperature measurements were carried out on the stretch between the Kozienice power plant and the Góra Kalwaria profile (*Fig.2*).
The following studies were carried out:

- expedition-type survey
- periodical survey
- everyday record of water temperature in selected cross-sections.

The expedition-type survey included:

1. Observations of temperature of natural and heated waters (intake and outlet).



expedition type survey
1000 periodical survey
39 400 daily temperature observations
WARSAW
NADWILANÓWKA
GÓRA KALWARIA
WARKA
KOZIENICE
DEBLIN
PUŁAWY
Świder
Wilga
Vistula
Wieprz

Fig. 2. Locations of Vistula thermal investigations cross-sections downstream of Kozienice Power plant

2. Measurements of the temperature and velocity distribution in the cross-section of the outlet channel.

3. Measurements of the temperature and velocity distribution in the cross-section at the distance of 100, 300, 1000, 9100, 12800, 39300 and 50800 m downstream of the heated waters discharge.

4. Power plant operational capacity record.

5. Meteorological data records

Periodical synoptic surveys included only the temperature and velocity distribution measurements in 1000 m profile downstream of the discharge and the observations mentioned in points 1, 2, 4, 5.
Fresh and heated waters temperature (p.1)were measured at 0.4 m below the surface by mercurial thermometers with the accuracy 0.1 deg. Measurements of the temperature distribution (p.2 and 3) in the cross-section were made by thermistor sensors, with the same accuracy. Temperature was measured in the profiles in each cross-section. The distance between profiles were: 20 m in the heated water stream and 50 m in the fresh water. In each profile the temperature was measured at 0.1 m and 0.4 m below surface, at every full meter and 0.1 above the bottom. The velocity distributions were measured by current meter type "Ott" (W.Germany) according to the Polish hydrological survey standard

Everyday record of water temperature was collected in three selected cross-sections with the distance from the discharge: 1000 m (Wiloskowice), 15500 m (Tarnów) and 39400 m (Królewski Las) respectively. Measurements were carried out at the depth of 0.4 m below the surface in three points: close to the banks and in the midstream by mercurial thermometers. The data were collected everyday at 7^{00} a.m; 12^{00} noon and 6^{00} p.m.

There were also pictures made by using the infrared imagery technique. There were three series of pictures made, covering the whole river stretch.

RESULTS

The Kozienice power plant capacity increased from 0 to 1600 MW during the time the project was being carried out. The monthly and annual mean, maximum and minimum of the operational capacity during 1973 to 1975 are given in table 10. The annual mean capacity in 1973 was 370 MW, in 1974 - 810 MW and in 1975 - 1150 MW. During summer months, the plant operated with lower capacity than the annual mean. The maximum of the daily mean capacity was recorded in November and December, 1975 (1520 MW).

17 expedition type surveys were carried out during 1973-1975 (1973 - 6 surveys, 1974 - 6 and 1975 - 5). Locations of the tested cross-section are shown in Fig.2. During the first year the stretch of only 12800 m was observed because of the small capacity of the plant. The stretch was enlarged to 35500 m in the last one. The obtained results are shown in table 11 and some of them (summertime) in figures Zac. 1, 2, 3, 4, 5, 6.

The results of periodical surveys are noted in table 12. The daily observations of water temperature in three Vistula profiles are given as monthly averages in table 13, fig. 3. Table 14, 15 and 16 show the results of the temperature evaluation by theoretical models.

A study of the water surface temperature distributions by the infrared imagery was carried out. This study was made downstream of the heated water discharge from the Kozienice power plant 3 times by using the thermoprofile THP-1 installed in an airplane:

September 3.1975 4^{26} - 4^{30} p.m
September 3.1975 6^{28} - 6^{37} p.m
September 4.1975 9^{07} - 9^{17} a.m

The flights were at the elevation of 800 m above the surface of the river with the speed of 290 km/h. The infrared pictures were made by the Vateal camera. An interpretation of the pictures is given in table 17 and in fig.4.

The time of movement of water particles detention time from Pulawy to the subsequent profiles along Vistula up to Warsaw in function of the water level at Pulawy gauge cross-section is shown on the graph (Fig.5).

Table 12. Monthly max., average and min. generating capacity of Kacherice Power plant

in each year of period 1973 to 1975

Year	Qualifi-cation of capacity	Months												Year
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1973	Average	89	80	130	230	310	370	460	440	480	560	740	640	370
1974		780	640	650	660	770	790	790	880	880	940	950	970	810
1975		1120	1240	1140	1200	1040	1090	1070	1060	1100	1210	1260	1330	1150
1973	Max.	180	180	290	490	480	530	580	580	600	960	960	970	960
1974		940	920	750	790	960	950	960	1160	1160	1150	1210	1160	1210
1975		1330	1580	1470	1470	1270	1290	1190	1270	1270	1430	1520	1520	1520
1973	Min.	40	30	12	110	170	180	190	200	230	280	380	320	33
1974		480	520	540	380	520	380	360	570	550	550	560	540	380
1975		670	700	540	720	640	700	660	780	590	820	760	920	540

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[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]
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[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]
[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]
[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]
[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]
[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

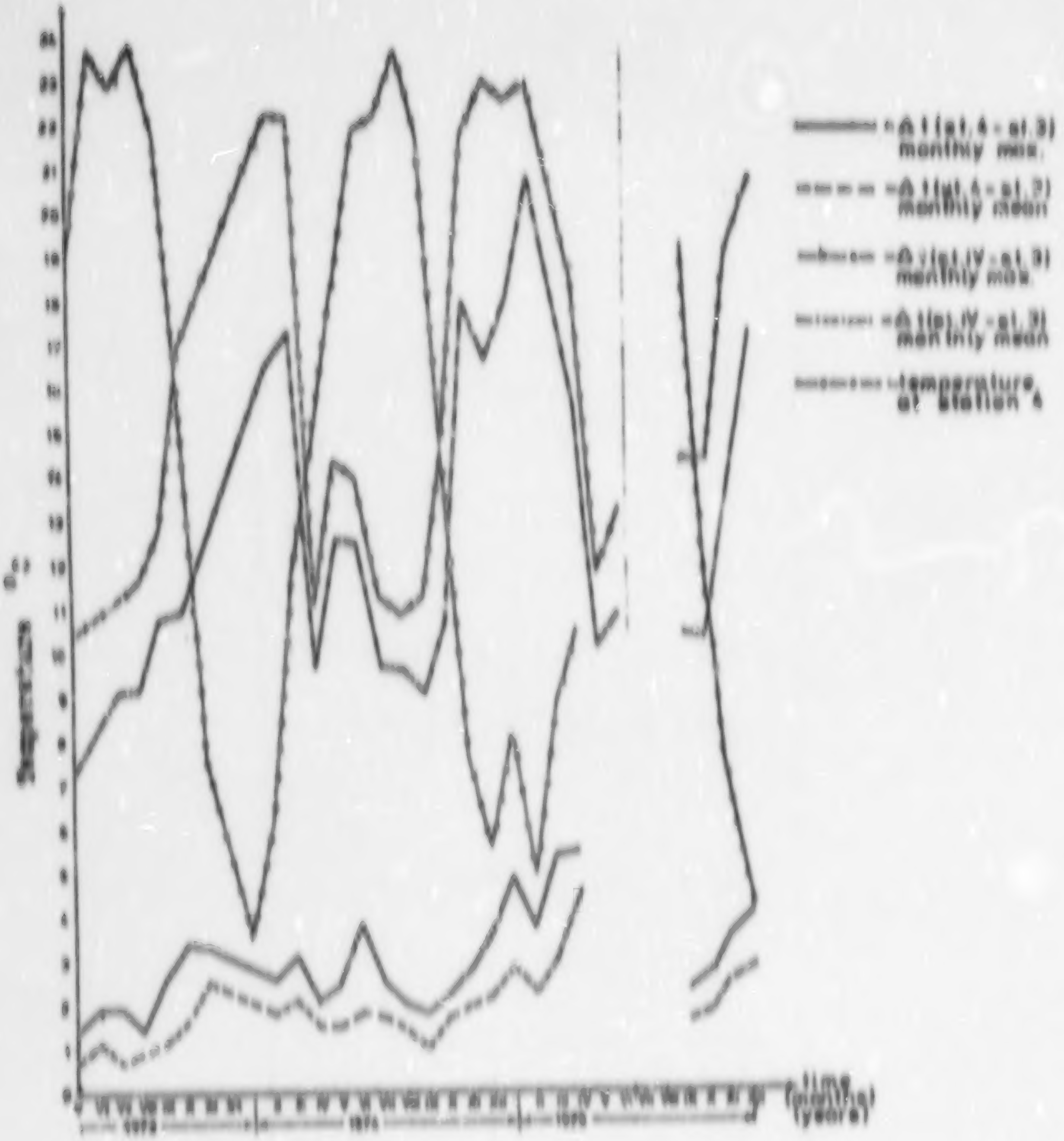


Fig.3. Variations of Vistula water temperature obtained from daily observations averages from 3 observations a day: at 7^{00} a.m., 12^{00} noon and 6^{00} a.m., at st. 4-averages from measurements in three points of river cross-section

Table 11 (continued)

Month year	h hour	Left bank 7,00	Left bank 13,00	Left bank 19,00	Midstream 7,00	Midstream 13,00	Midstream 19,00	Right bank 7,00	Right bank 13,00	Right bank 19,00	Daily averages left	Daily averages mid.	Daily averages right	[illegible]	Max. temp.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 15. Comparison of T_{av} values evaluated by Jaworski's method with those calculated basing on surveys results

Date	x	Survey	Model
4.26-27,1973	100	11.8	11.6
	300	11.7	11.6
	1000	11.7	11.6
	9100	11.6	11.2
5. 7-9 ,1973	100	16.7	16.5
	300	16.8	16.4
	1000	16.7	16.3
	9100	16.5	16.1
5.17-18,1973	100	14.6	14.4
	300	14.6	14.3
	1000	14.6	14.2
	9100	14.5	14.0
7.17-18,1973	100	24.0	23.9
	300	23.8	23.9
	1000	23.8	23.6
	9100	23.8	23.2
7.26-27,1973	100	19.3	18.7
	300	18.8	18.7
	1000	18.8	18.6
	9100	18.9	18.5
	12800	19.0	18.4
8. 6-7 ,1973	100	25.0	24.4
	300	24.6	24.3
	1000	24.3	24.3
	9100	24.6	24.1
	12800	24.8	24.0
6. 3-4 ,1974	300	10.8	10.4
	1000	10.6	10.3
	9100	10.6	10.0
	12800	11.0	10.0
6.17-18,1974	300	10.3	10.0
	1000	10.5	9.8
	9100	9.5	9.5
	12800	9.4	9.6
	22800	9.6	9.2

Table 15 (continued)

Date	x	Survey	Model
5, 2-3 ,1974	300	13.9	13.6
	1000	14.2	13.6
	2400	13.0	13.5
	9100	14.0	13.3
	12800	13.4	13.2
	35500	13.3	13.0
7,24-26,1974	300	19.4	19.0
	1000	19.2	18.9
	9100	19.1	18.8
	35500	19.1	18.6
8, 5-7 ,1974	300	23.9	23.3
	1000	23.8	23.2
	9100	23.8	23.0
	12800	23.8	22.9
	35500	23.3	22.7
8,19-21,1974	300	23.6	23.1
	1000	23.5	23.0
	9100	23.5	22.7
	12800	23.5	22.7
	35500	22.9	22.4
5, 5-7 ,1975	1000	12.6	23.2
	4000	12.5	23.1
	12800	12.4	22.9
	35500	12.4	22.7
	90800	12.3	22.6
5,21-24,1975	300	19.8	19.6
	1000	19.6	19.3
	12800	19.8	19.2
	35500	19.6	18.9
	90800	19.1	18.8
8, 5-7 ,1975	300	22.1	21.9
	1000	22.1	21.8
	12800	22.0	21.5
	35500	21.9	21.2
	90800	21.8	21.1

Table 15 (continued)

Date	z	Survey	Model
8,19-22,1979	200	22.5	22.0
	1000	22.1	21.8
	4000	21.8	21.6
	12800	21.7	24.4
	35900	21.5	21.1
	90800	21.3	21.0
9, 2-5 ,1979	300	22.6	22.3
	1000	22.6	22.2
	4000	22.4	22.0
	12800	22.2	21.7
	35900	21.8	21.6
	90800	21.8	21.3

Table 16. Comparison of $T_{SS,i}$ values evaluated by [illegible] method with those calculated basing on surveys results

Date	X	$T_{SS,i}$ Survey	$T_{SS,i}$ Model	R
1	2	3	4	5
6,26-27,1973	100	[illegible]	[illegible]	[illegible]
	300	[illegible]	[illegible]	
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
5, 7-8 ,1973	100	[illegible]	[illegible]	[illegible]
	300	[illegible]	[illegible]	
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
6,17-18,1973	100	[illegible]	[illegible]	[illegible]
	300	[illegible]	[illegible]	
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
7,17-18,1973	100	[illegible]	[illegible]	[illegible]
	300	[illegible]	[illegible]	
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
7,25-27,1973	100	[illegible]	[illegible]	[illegible]
	300	[illegible]	[illegible]	
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
8, 6-7, 1973	100	[illegible]	[illegible]	[illegible]
	300	[illegible]	[illegible]	
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
6, 3-4, 1974	300	[illegible]	[illegible]	[illegible]
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
6,17-18,1974	300	[illegible]	[illegible]	[illegible]
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
5, 2-3, 1974	300	[illegible]	[illegible]	[illegible]
	1000	[illegible]	[illegible]	
	3000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
7,26-28,1974	300	[illegible]	[illegible]	[illegible]
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
8, 5-7, 1974	300	[illegible]	[illegible]	[illegible]
	1000	[illegible]	[illegible]	
	5170	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
8,19-21,1974	300	[illegible]	[illegible]	[illegible]
	1000	[illegible]	[illegible]	
	5100	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
5, 5-7, 1975	1000	[illegible]	[illegible]	[illegible]
	4000	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
	50000	[illegible]	[illegible]	

Table 16 (continued)

Date	Z	V_{ms} Survey	V_{ms} Model	R
1	2	3	4	5
5,21-25,1973	200	19,8	19,7	1,01221
	1000	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
	50000	[illegible]	[illegible]	
6, 3-7, 1973	200	[illegible]	[illegible]	1,18169
	1000	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
	50000	[illegible]	[illegible]	
6,18-22,1973	200	[illegible]	[illegible]	0,87133
	1000	[illegible]	[illegible]	
	5000	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	25000	[illegible]	[illegible]	
	50000	[illegible]	[illegible]	
9, 3-8, 1973	200	[illegible]	[illegible]	0,88738
	1000	[illegible]	[illegible]	
	5000	[illegible]	[illegible]	
	10000	[illegible]	[illegible]	
	15000	[illegible]	[illegible]	
	50000	[illegible]	[illegible]	

Table 17. River water surface temperature interpreted from infrared pictures. September 5th,1975, 4.00 a.m.

X	Y	T
0	97.5	21.9
	205.0	22.0
	230.0	21.7
	375.0	21.7
800	25.0	23.4
	122.5	23.1
	175.0	21.7
	280.0	21.7
	342.5	21.7
	390.0	21.9
1000	20.0	23.4
	137.5	23.6
	205.0	23.0
	262.5	21.7
	400.0	21.7
1700	10.0	23.4
	172.5	23.5
	375.0	21.7
	480.0	21.7
2500	10.0	23.2
	75.0	23.2
	287.5	23.3
	372.5	23.0
	472.5	23.3
	675.0	22.7
	712.5	23.0
	762.5	23.0
3100	50.0	23.3
	287.5	23.4
	447.5	23.2
	580.0	21.7
	675.0	21.7
	745.0	21.7
4000	20.0	23.3
	50.0	23.4
	80.0	23.4
	250.0	23.4
	330.0	23.2
	420.0	22.0
	500.0	22.7
	595.0	21.7
4700	10.0	23.3
	75.0	23.4
	130.0	23.3
	300.0	22.0
	472.5	21.7
	500.0	21.7
	612.5	21.7
5300	17.5	23.4
	72.5	23.3
	135.0	23.1
	400.0	22.0
	575.0	21.7
	617.5	21.7
	737.5	21.7
6600	25.0	23.4
	75.0	23.0
	157.5	22.0
	567.5	21.7
	755.0	21.7
7500	20.0	23.2
	72.5	23.4
	150.0	22.0
8300	20.0	23.4
	52.5	23.3
	97.5	23.0
	145.0	22.0
8900	25.0	23.3
	50.0	23.3
	127.5	21.8
	412.5	21.7
	525.0	21.7
	637.5	21.7
	712.5	21.7

Table 17 (continued)

X	Y	T
9400	25.0	23.3
	112.5	23.3
	200.0	22.7
	255.0	22.0
	305.0	21.7
	355.0	21.7
	475.0	21.7
	920.0	21.7
9900	205.0	23.8
	312.5	23.0
	430.0	21.9
	500.0	21.7
	605.0	21.7
10300	227.5	23.8
	277.5	23.3
	490.0	21.9
	572.5	21.7
	647.5	21.7
10700	200.0	23.0
	337.5	23.2
	385.0	23.1
	455.0	22.1
	555.0	21.7
	672.5	21.7
	770.0	21.7
11300	300.0	23.2
	365.0	23.2
	375.0	21.9
	467.5	22.7
	600.0	22.0
	762.5	21.7
	820.0	21.7
	887.5	21.7
11900	55.0	23.0
	227.5	23.0
	520.0	22.8
	570.0	22.8
	637.5	21.7
	737.5	21.7
	800.0	21.7
12500	37.5	23.6
	130.0	23.4
	255.0	23.3
	500.0	23.2
	625.0	23.0
	712.5	22.8
	772.5	21.7
	825.0	21.7
13200	45.0	23.0
	122.5	23.2
	180.0	23.0
	300.0	22.0
	375.0	21.7
	445.0	21.7
13500	25.0	23.1
	167.5	21.7
	322.5	21.7
	372.5	21.7
	430.0	21.7
14000	150.0	22.7
	222.5	22.0
	275.0	21.7
	422.5	21.7
	495.0	21.7
14400	180.0	22.7
	365.0	22.0
	422.5	21.7
	522.5	21.7
	575.0	21.7
15000	5.0	23.4
	52.5	23.2
	137.5	23.2
	205.0	22.0
	255.0	21.7
	287.5	21.7
	375.0	22.0
	420.0	21.7
	462.5	21.7
	607.5	21.7
	662.5	21.7
	755.0	21.7
15700	475.0	23.0
	550.0	23.1
	597.5	23.3
	647.5	23.3
	680.0	23.3
	705.0	22.7
	730.0	21.6
	822.5	21.7
	920.0	21.8

Table 17 (continued)

X	Y	T
16500	272.5	23.3
	487.5	23.3
	500.0	23.3
	552.5	23.2
	650.0	23.1
	737.5	22.8
	825.0	21.9
	862.5	21.8
17300	580.0	23.3
	612.5	23.3
	620.0	23.0
	695.0	23.2
	750.0	23.3
	797.5	23.2
	850.0	23.2
	912.5	23.0
	967.5	22.0
	1020.0	21.9
	1100.0	21.8
18200	372.5	23.0
	490.0	22.7
	587.5	22.7
	687.5	22.3
	822.5	21.7
	895.0	21.7
19200	612.5	22.0
	612.5	22.0
	672.5	21.7
	775.0	21.7
	887.5	21.7
19900	130.0	23.3
	350.0	23.2
	475.0	22.0
	597.5	21.7
	712.5	21.7
	797.5	21.7
20600	12.5	23.2
	100.0	23.2
	175.0	23.0
	287.5	23.0
	412.5	23.0
	470.0	22.0
	525.0	21.7
	580.0	21.7
21300	150.0	22.3
	225.0	22.3
	305.0	22.7
	362.5	21.8
	405.0	22.3
	480.0	22.3
	537.5	21.8
	600.0	22.0
	687.5	21.7
21900	312.5	22.0
	412.5	21.7
	495.0	21.7
	575.0	21.7
	625.0	21.7
	672.5	21.7
	745.0	21.7
22700	312.5	23.0
	395.0	22.7
	475.0	21.8
	562.5	21.7
	625.0	21.7
	730.0	21.7
	797.5	21.7
	930.0	21.7
	962.5	21.7
23500	37.5	23.0
	512.5	22.0
	675.0	22.3
	825.0	21.7
	925.0	21.7
24100	20.0	23.0
	125.0	22.7
	225.0	22.0
	325.0	22.0
	395.0	22.0
	450.0	22.0
	737.5	21.7
24700	25.0	22.0
	125.0	21.9
	220.0	21.9
	350.0	21.8
	397.5	21.7
	500.0	21.7
	635.0	21.7

Table 17 (continued)

X	Y	T
25400	30.0	22.0
	250.0	22.0
	355.0	21.7
	500.0	21.7
26000	20.0	23.0
	250.0	22.7
	355.0	22.7
	445.0	21.9
	512.5	21.9
27100	22.5	23.0
	112.5	22.8
	225.0	22.3
	370.0	22.0
	422.5	21.9
	455.0	21.8
27700	25.0	22.0
	112.5	22.0
	180.0	22.0
	237.5	22.0
	325.0	22.0
	450.0	21.7
28200	25.0	22.0
	100.0	22.3
	197.5	21.7
	312.5	21.7
	387.5	21.7
	520.0	21.7
	630.0	21.7
28700	30.0	22.7
	120.0	21.7
	187.5	21.7
	255.0	21.7
	322.5	21.7
	375.0	21.7
	400.0	23.0
29300	25.0	22.3
	162.5	22.3
	270.0	22.3
	387.5	21.7
	520.0	21.7
	570.0	21.7
29900	112.5	22.3
	175.0	22.0
	220.0	22.7
	370.0	22.0
	425.0	21.7
	540.0	21.7
30900	35.0	21.7
	100.0	22.7
	150.0	21.7
	245.0	21.7
	320.0	21.7
31800	37.5	22.0
	137.5	21.9
	230.0	22.0
	305.0	21.7
	370.0	21.7
	430.0	21.7
33300	25.0	21.7
	147.5	21.8
	255.0	21.7
	362.5	21.7
	500.0	21.7
34900	22.5	21.7
	100.0	21.6
	170.0	21.7
	275.0	21.7
	330.0	21.7
35500	20.0	21.7
	122.5	21.6
	200.0	21.7
	300.0	21.7
	20.0	21.7
	197.5	21.7
	325.0	21.7
	362.5	21.9
	405.0	21.7
36200	20.0	21.9
	150.0	21.9
	187.5	21.9
	305.0	21.9
	495.0	21.8

Table 17 (continued)

X	Y	T
37100	25,0	21,9
	275,0	21,9
	475,0	21,8
37900	25,0	21,9
	80,0	22,0
	125,0	22,0
	155,0	22,0
	300,0	22,0
	470,0	22,0
38400	12,5	21,7
	55,0	21,7
	125,0	21,7
	225,0	22,0
	325,0	21,8
	430,0	21,8
	550,0	21,7
39000	15,0	21,7
	367,5	21,9
	572,5	21,7
39900	187,5	21,7
	325,0	21,7
	550,0	21,7
40200	25,0	21,7
	250,0	21,9
	400,0	21,7
	470,0	21,7
	525,0	21,7
41300	25,0	21,7
	137,5	21,7
	300,0	21,5
	347,5	21,7
	397,5	21,7
	480,0	21,7
	550,0	21,7
42000	30,0	21,8
	250,0	21,7
	500,0	21,7
43000	25,0	22,0
	375,0	21,8
	587,5	21,8
43900	30,0	21,7
	335,0	21,7
	555,0	21,7
45000	12,5	21,7
	147,5	21,7
	262,5	21,7
	325,0	21,7
	580,0	21,7
	612,5	21,7
	642,5	21,7
45900	30,0	21,7
	180,0	21,7
	320,0	21,7
	375,0	21,7
47000	-	21,7
	-	21,7
	-	21,7
	-	21,7
	-	21,7
	-	21,7

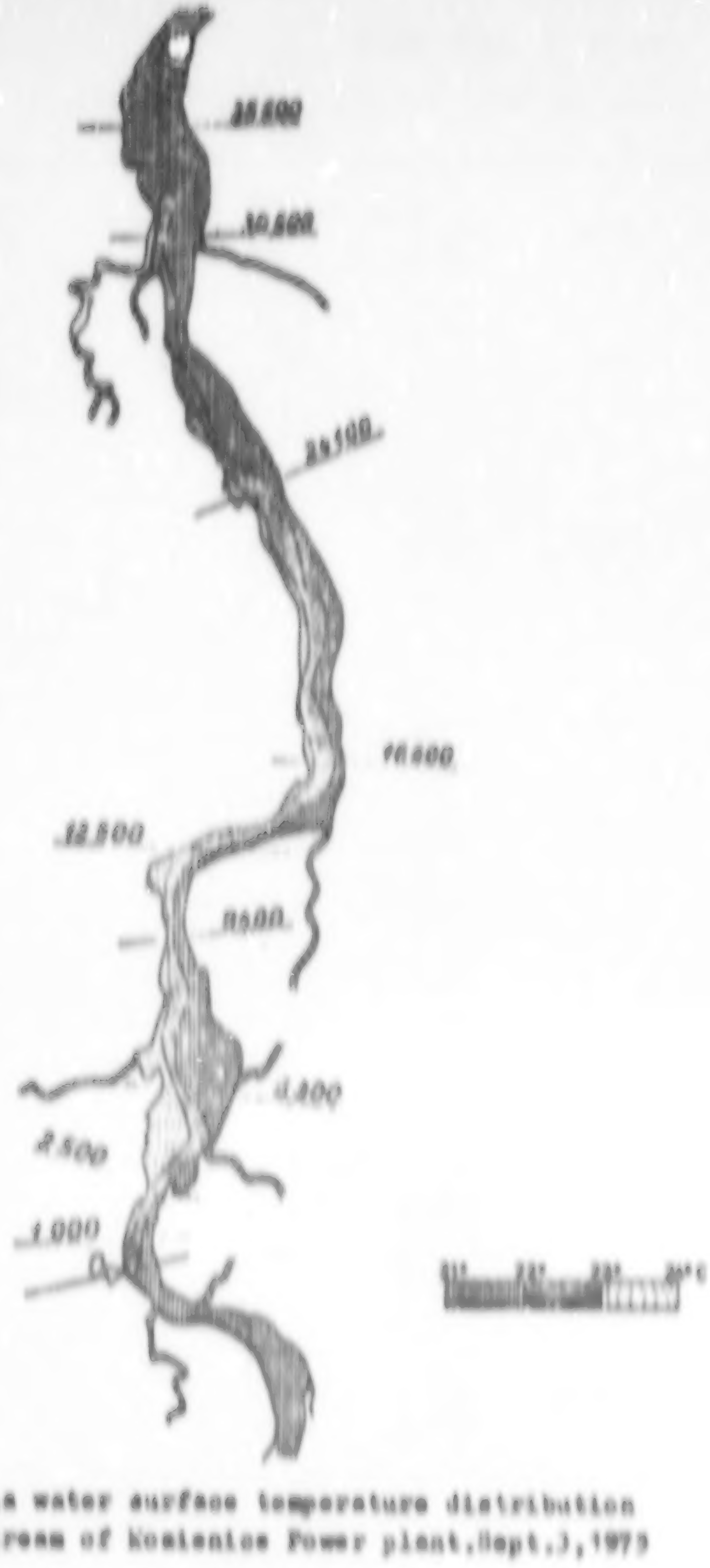
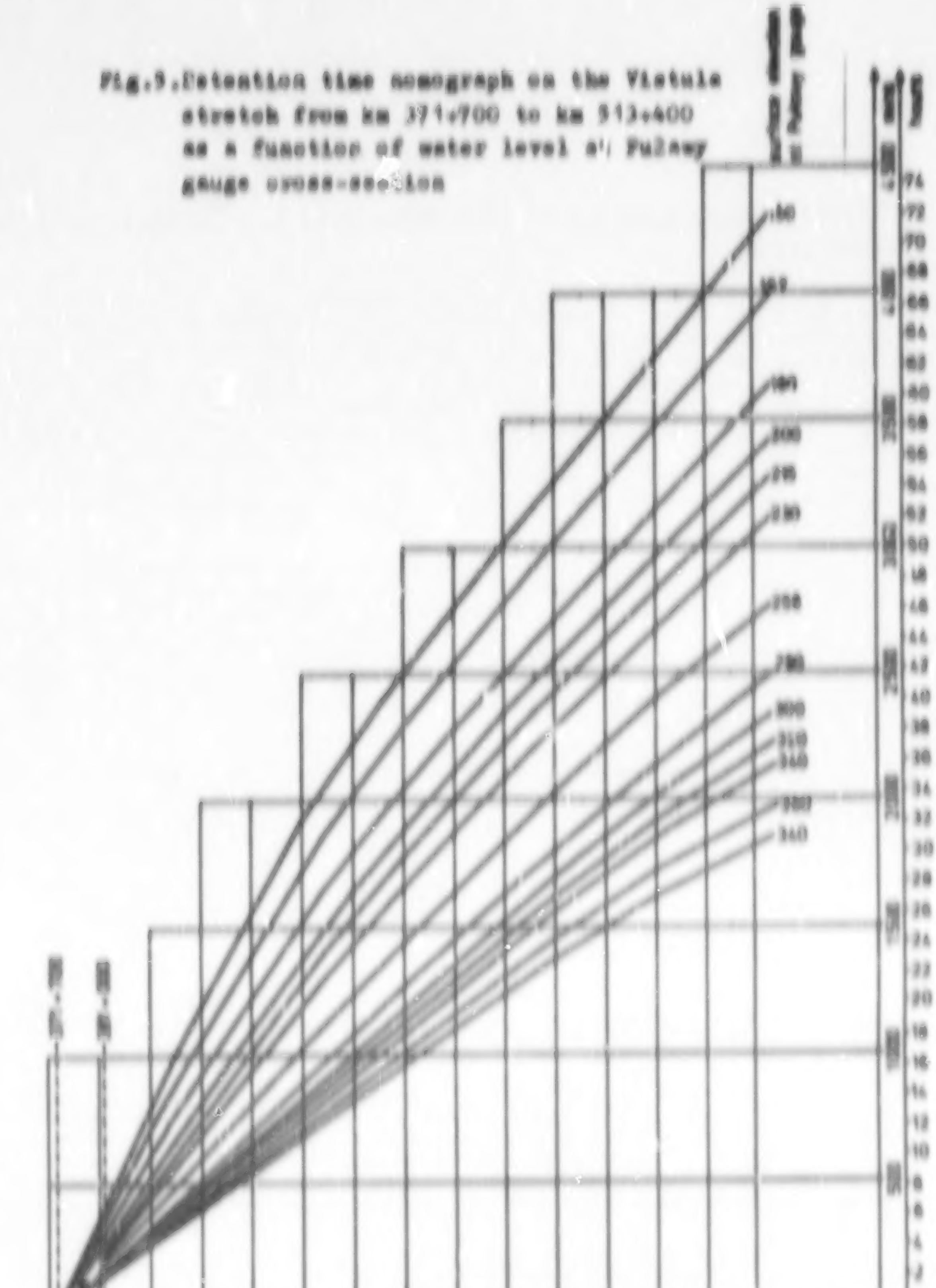

35.500
30.500
24.100
16.600
12.500
11.600
4.400
2.500
1.000

Fig. 4. Vistula water surface temperature distribution downstream of Kozienice Power plant,Sept.3,1975

Fig.5.Detention time nomograph on the Vistula stretch from km 371+700 to km 513+400 as a function of water level at Pulawy gauge cross-section



DISCUSSION

Thermal regime of Vistula water downstream of Kozienice Power plant

One can see from the obtained results that in all cross-sections the lateral stratification (two-streams system) exists. However, the discharge channel was fully mixed - temperature difference in the cross-section was less than 0,5 °C. The heated water stream can be easy separated at a distance of 12800 m downstream from the discharge of the power plant with 6 units operating. Max. temperature rise at the distance of 1000 m downstream was observed on September 17, 1973 and was equal to 7,7 °C. The average in this cross-section was 1,4 °C. The Plant was operating then with the capacity 1150 MW, discharging 11% of the total rate of stream flow equal to 404 m^3/s.

In the further stretch of 12800 m downstream from the source, the heated water stream is observed on the whole width of the river. The difference of temperature between the two banks did not exceed 0,5 °C. The average rise of temperature on the stretch between the source and the profile of 1000 m downstream never exceeded 1,5 °C - observation in the cross-section 1000 m, April 17-18, 1974, capacity 790 MW, heated waters discharge 23,1 m^3/s and flow 200 m^3/s.

The section between the source and the 1000 m profile downstream is the zone of intensive mixing and cooling. A smaller temperature gradient is observed at the last part of the observed stretch. In the cross-section 50800 m downstream from the discharge the temperature rise of only 0,3 °C is observed. That value is close to the accuracy of the instruments. Therefore, the stretch of the length of 50 km has to be recognized as affected by the Power plant under existing conditions. The infrared pictures confirmed that, too.

The influence of heated waters on the ice phenomena in the river cannot be estimated properly, because these phenomena did not occur distinctly in the profiles above the discharge.

The critical periods for cooling process are given in table 18. The max. water temperature close to the source bank at the distance of 1000 m downstream occurred on August 11, 1973 at 12^{00} noon and 6^{00} p.m. and was equal to 26,8 °C. At the same time the temperature of fresh water was 22,3 °C. The power plant operated with the 1018 MW capacity and the flow was equal to 526 m^3/s.

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Such high temperatures were not observed in previous years, because full capacity was not put into operation.

Estimation of the models

The estimation of the models was done on the basis of 17 expedition type surveys and 19 periodical surveys. The results of computations of the temperature distributions were compared with measured values. Theoretical and measured values for the cross-section of 1000 m downstream of the Plant are set together in table 19. One can see that the Jaworski's method is less accurate. The average error is 0,4 °C for the mean temperature, 0,18 °C and 0,22 °C are the errors for the "Energoprojekt" and Edinger-Polk methods, respectively. These results can be accepted as satisfactory, however, the max. difference was much larger 0,8 °C

Rather poor agreement between the computed and measured lateral temperature distribution in the cross-sections was obtained. That may be explained as follows:

- During observation period the critical conditions did not occur. The ratio of the heated waters quantity to the rate of river flow was small and ranged from 1,0 % to 14,3 %
- There were difficulties with proper determination of the characteristic numbers for each cross-section e.g. area of the fresh and heated water streams etc , because of complicated morphometry of the river bed.
- Lack of river training structures.

Summarising, one can state that at the actual technical level the last two methods are satisfactory for determination of the average temperature in a river cross-section.

In order to properly determine the lateral temperature distribution a new model should be prepared. That model should be probably three - dimensional and discreet (river stretch should be divided into small uniform sections), because a continuous model offers poor results. As an initial equation e.g. the Edinger-Polk method or any other solution of the energy conservation law may be applied.

Table 19. Comparison of mean water temperature value in Vistula cross-section 1000 m downstream the discharge evaluated by "Energoprojekt" s, Jaworski's and Edinger-Polk's methods with those obtained from surveys results.

Date	Mean temperature in cross-section 1000 m downstream discharge			
	Survey	"Energoprojekt's" method	Jaworski's method	Edinger-Polk's method
4.26,1973	11,7	11,6	11,4	11,6
5.7, 1973	16,7	16,6	16,3	16,6
5.17,1973	14,6	14,5	14,2	14,6
7.17,1973	23,8	23,7	23,4	23,8
7.26,1973	18,8	18,9	18,6	18,9
8.6, 1973	24,5	24,5	24,3	24,6
4.3, 1974	10,8	10,6	10,3	11,0
4.17,1974	10,5	10,1	9,9	10,2
5.2, 1974	14,2	13,8	13,6	13,9
7.24,1974	19,2	19,2	18,9	19,3
8.5, 1974	23,8	23,5	23,2	23,6
8.19,1974	23,3	23,3	23,0	23,4
5.9, 1975	12,6	12,5	12,2	12,6
5.21,1975	19,6	19,8	19,5	19,4
8.5, 1975	22,1	22,1	21,8	21,9
8.19,1975	22,1	22,1	21,8	21,7
9.2, 1975	22,6	22,5	22,2	22,2

SECTION 6

HYDROCHEMICAL STUDIES

EFFECTS OF THE HEATED WATERS DISCHARGE ON THE VISTULA WATER QUALITY

Methods

The hydrochemical investigations of the Vistula water and its tributaries were carried out in the stretch of the river from Puławy to Warsaw (fig.6, tabl.20).
Usually the samples for the investigations were taken from the left bank of the Vistula river at places of distinct current. Only at station No 2 the samples were taken at the right river bank. At stations in the vicinity of the thermal water discharge from the power plant, namely at stations 3, 4 and 4a the samples were taken at three points in cross-section (the left bank, the middle and the right bank). After June, 1974, the samples were taken occasionally at three points in cross-section at other stations too.

The samples for investigations were taken once or twice a month. The samples were taken first at station 1, and during the next two or three days according to the rate of water flow the sampling continued up to station no.9.

In order to observe the changes in the Vistula water quality close to the power plant Kozienice for twenty four hours a day, samples were taken every two hours.

Twice a year, in spring and fall, sampling was synchronized with the speed of the water flow, which was calculated according to the nomogram of the flow time for the section from Puławy to Warsaw and for different water levels at the Puławy water gauge (29). During these investigations at each station along the Vistula river the samples were taken at three points at cross-section.

Usually samples were taken from flowing water at 30 cm below the water surface.

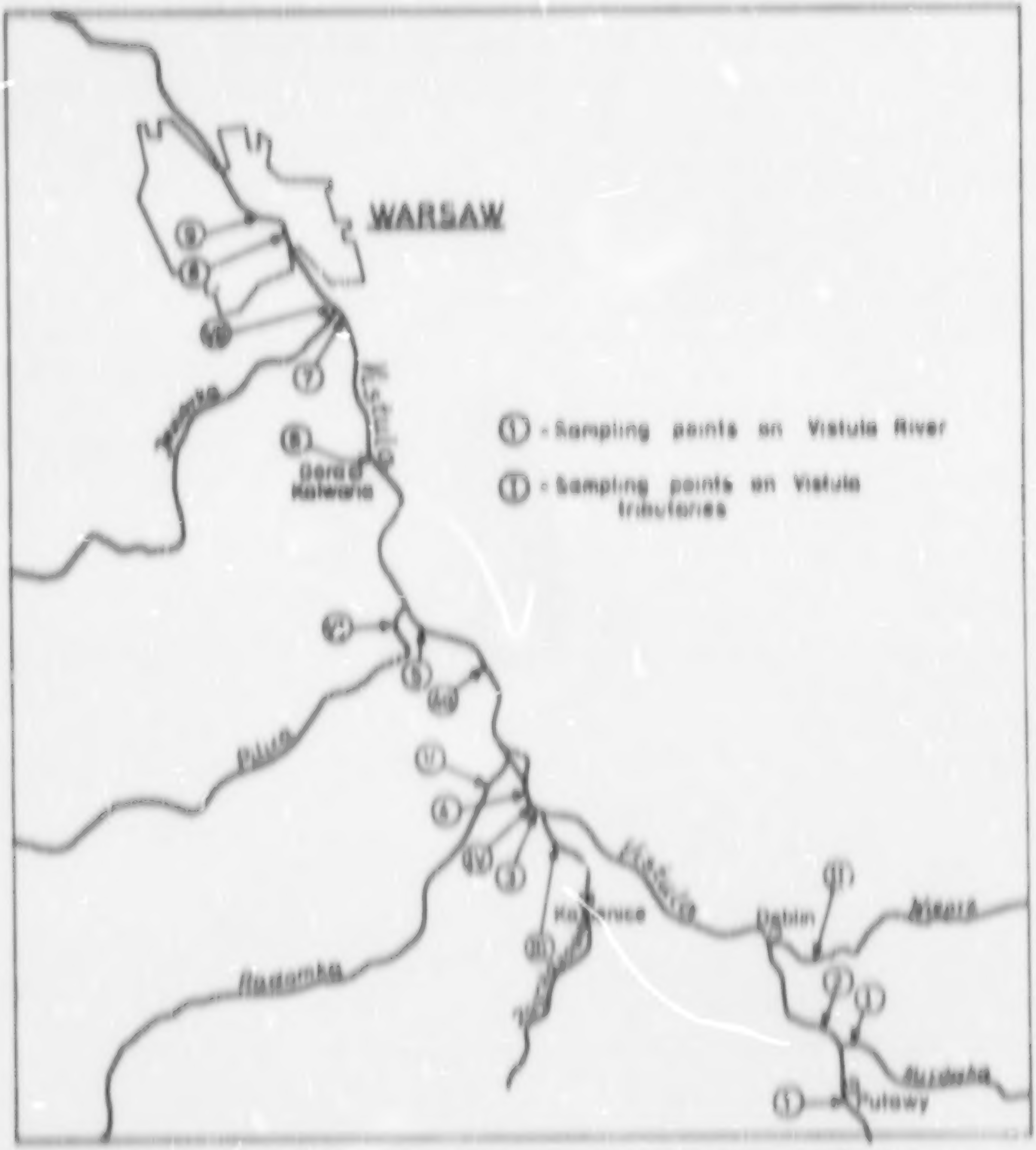

WARSAW
Vistula
Jeziorka
Gora Kalwaria
Pilica
Radomka
Kozienice
Deblin
Wieprz
Kurowka
Pulawy
① - Sampling points on Vistula River
(I) - Sampling points on Vistula tributaries

Fig. 6. Location of sampling points on Vistula River and its tributaries

Table 20. List of localisation of the sampling stations

No	Sampling points	Km of the River	Bank
	The Vistula River		
1	Above Puławy	371.0	left
2	Below Puławy	381.0	right
3	Above Kozienice power station	426.0	cross-section
4	Below Kozienice power station	428.5	cross-section
4a	Below Radomka River mouth	438.0	cross-section
5	Above Pilica River mouth	455.0	left
6	Góra Kalwaria	476.0	left
7	Above Jeziorka River mouth	493.0	left
8	Above Siekierki power plant	504.0	left
9	Warsaw - Czerniaków	509.0	left
	Tributaries	Km of Vistula River	
I	Kurówka River mouth	378.1	right
II	Wieprz River mouth	393.7	right
III	Zagożdżonka River mouth	425.0	middle
IV	Discharge of heated waters from the Kozienice power plant to the channel	426.5	
IVa	Outlet of heated water channel into the Vistula river		
V	Radomka River mouth	431.8	right
VI	Pilica River mouth	457.0	right
VII	Jeziorka River mouth	493.7	right

The physical and chemical analyses of the samples covered the following parameters: temperature, turbidity, color, conductivity, odor, pH, dissolved oxygen, BOD_5, COD, ammonia, nitrite, nitrate and organic nitrogen, total, volatile and fixed residue, orthophosphate, total phosphate, and during the first two years, phenols.

The methods of preservation of the samples and methods of physical and chemical analysis were performed in accordance with the Analytic Manual for Determination of Pollution in Surface Waters and Wastewaters, elaborated by the Institute of Water Economy in 1972 (30), and they are, in a large extent, similar to the methods suggested by Standard Methods (31).

The water temperature was measured directly in water with the accuracy of 0.1 °C. Immediately after the samples had been taken, they were fixed according to the determination: dissolved oxygen - with a solution on manganese sulphate and alkali-iodide-azide reagent; COD - with a concentrated sulphuric acid; nitrogen compounds, dry residue and phosphates - with chloroform; phenols - with a solution of manganese sulphate and phosphoric acid.

The samples were transported daily to the laboratory and stored at low temperature until the time of analysis. The determination performed from unpreserved samples was made within 24 hours after sampling.

All the determinations were performed in two parallel repetitions. When there was a too large discrepancy between results, a third determination was made. The average from the two most similar results was considered a final result. See section on Precision of Analytical Methods (enclosure 7, in Supplement to this report).

The analyses were performed in the following manner:

- turbidity, measured with the "Hach" turbidity meter;

- colour, defined on the basis of visual comparison with the scale of platinum-cobalt standards;

- conductance, measured with the conductivity meter "Radiometer";

- odor, using the organoleptic method, according to intensity scale of six degrees;

- pH, using the potentiometric method with a pH-meter, Type LBST-8;

- dissolved oxygen, using the modified method of Winkler-Alsterberg;

- BOD_5, using the method of dilution;
- COD, with bichromate of potassium two hours reflux;
- ammonium nitrogen, by the colorimetric Nessler method using the "Specol" photocolorimeter;
- nitrite nitrogen, using the Gress-Ilosvay's colorimetric method, with a photocolorimeter of the "ZAL" type;
- nitrate nitrogen, using the colorimetric method with phenoldisulphonic acid, with a photocolorimeter of the "ZAL" type;
- organic nitrogen, using the Kjeldahl method;
- orthophosphate, using the colorimetric method with ammonium molibdate;
- total phosphate, as above, after dry combustion of the samples;
- dry residue, at 100°C, using the weighing method;
- phenols, using the colorimetric method with 4-aminoantypiryn on autoanalyzer "Technicon".

Results

The research on the water quality of Vistula river and its tributaries was carried out from January 1973 to December 1975, fifteen to sixteen times per year. Additionally, twenty four-hour investigations were carried out, concerning such parameters as: temperature, D.O, BOD_5, NO_2, NH_3.

All results of measurements are provided in a separate U.S. Environmental Protection Agency report entitled the *Supplement to "Studies on the Effects of Heated Waters Discharged from the Kozienice Power Plant on the physico-chemical processes in the Vistula River and on the Water Quality"*, Research Grant No. PR-05-532-5. Basic Data. Warsaw, Poland 1976. This supplement is available from NTIS; access number same as this report with suffix "B".

Discussion

The changes of water quality along the Vistula river in the years 1973 to 1975 -

The evaluation of the water quality changes along the Vistula river is based on annual average and extreme results of water analyses performed during 1973 to 1975. (Enclosure 8-99). In the tables 21-23 annual average values of more important parameters are given.

Table 21. Averages of results of Vistula river and its tributaries water quality measurement year 1973

Sampl. sta- tions	Temp. of water °C	DO	BOD_5	COD	NH_3-N	NO_2-N	NO_3-N	Org. N	Residue total
		mg/l O_2			mg/l N				mg/l
1	9.8	9.3	4.3	26.8	1.30	0.027	0.72	1.91	539
2	10.6	8.6	3.7	29.5	2.08	0.047	0.90	2.44	529
3	9.9	9.7	3.2	25.7	1.40	0.033	0.86	1.80	511
4	11.1	9.3	4.7	23.0	1.39	0.038	0.86	1.79	516
4a	10.8	9.4	3.8	26.9	1.39	0.039	0.90	1.90	495
5	9.9	10.1	3.6	28.5	1.40	0.033	0.87	1.53	500
6	9.7	10.4	3.1	28.7	1.17	0.025	0.77	1.58	465
7	10.4	10.3	4.8	26.8	1.19	0.025	0.76	1.59	473
8	12.0	10.1	5.2	25.8	1.03	0.028	0.73	1.28	475
9	10.2	10.3	4.8	27.6	1.18	0.025	0.75	1.31	473
I	15.8	7.3	6.5	29.6	15.4	0.416	4.9	16.5	558
II	11.8	8.6	3.8	28.7	1.00	0.036	0.58	1.70	371
III	9.4	7.8	2.5	19.7	0.48	0.048	2.95	1.58	372
IV	22.1	8.5	5.4	25.8	1.30	0.068	0.86	1.47	505
V	9.4	6.9	7.3	36.0	2.73	0.036	0.28	2.28	321
VI	10.2	9.8	3.3	24.9	0.33	0.009	0.33	1.68	293
VII	12.2	7.0	13.3	30.4	0.80	0.111	0.50	1.97	411

Table 22. Averages of results of Vistula river and its tributaries water quality measurement year 1974

Sampl. sta- tions	Temp. of water °C	DO	BOD$_5$	COD	NH$_3$-N	NO$_2$-N	NO$_3$-N	Org. N	Residue total
		mg/l O$_2$			mg/l N				mg/l
1	10,5	9,8	6,0	23,6	1,13	0,026	0,99	1,26	494
2	10,5	9,8	5,0	23,4	1,75	0,048	1,20	1,63	486
3	10,0	10,1	4,2	25,9	1,08	0,024	1,10	1,35	486
4	12,1	9,7	4,2	24,5	1,07	0,030	1,00	1,46	490
4a	11,1	9,7	4,7	25,6	1,09	0,031	0,99	1,31	467
5	11,0	10,9	4,8	23,2	1,02	0,031	0,98	1,33	471
6	10,4	11,0	4,6	23,7	0,84	0,021	0,89	1,47	436
7	9,8	10,1	4,2	26,0	0,80	0,024	0,95	1,38	440
8	10,0	10,0	4,6	25,6	0,77	0,025	1,00	1,43	443
9	10,1	10,2	4,8	27,4	0,78	0,023	0,97	1,36	439
I	14,7	7,7	86	27,1	12,7	0,444	4,6	10,3	513
II	11,2	7,8	3,8	29,5	0,89	0,033	0,48	1,35	361
III	9,9	7,2	2,0	21,3	0,62	0,106	3,63	1,25	393
IV	20,8	8,9	4,7	23,5	1,00	0,035	1,12	1,42	473
V	10,1	6,8	6,0	34,7	2,36	0,050	0,26	1,93	319
VI	10,2	10,3	3,1	23,0	0,43	0,009	0,40	1,29	296
VII	9,7	7,7	9,0	40,0	0,92	0,061	0,86	1,84	425

Table 23. Averages of results of Vistula river and its tributaries water quality measurement year 1973

Sampl. stations	Temp. of water °C	DO	BOD_5	COD	NH_3-N	NO_2-N	NO_3-N	Org. N	Residue total
		mg/l O_2				mg/l N			mg/l
1	11,1	9,8	3,5	21,2	0,78	0,027	0,88	0,97	464
2	11,4	9,9	4,1	19,4	1,32	0,051	1,00	1,22	459
3	10,8	10,4	3,6	18,7	0,79	0,037	0,99	0,96	454
4	13,5	10,1	3,6	18,7	0,76	0,035	1,00	1,02	453
4a	12,3	10,1	4,2	20,3	0,82	0,038	0,96	1,11	431
5	12,0	10,3	3,9	21,2	0,77	0,035	1,00	0,99	447
6	11,1	10,6	4,0	19,2	0,66	0,030	0,92	1,16	406
7	11,0	11,0	4,0	19,8	0,61	0,028	0,97	1,21	424
8	11,1	11,1	4,6	20,7	0,63	0,027	0,93	1,18	435
9	11,2	11,1	4,4	20,9	0,63	0,028	0,94	1,20	428
I	15,6	7,6	12,7	22,8	12,9	0,451	4,10	11,0	516
II	11,0	9,6	3,3	24,9	0,49	0,028	0,34	1,27	342
III	10,6	7,7	2,4	18,3	0,61	0,121	4,38	1,07	603
IV	22,8	9,3	3,4	17,7	0,76	0,051	1,02	1,08	447
V	10,9	7,1	9,3	33,7	2,29	0,036	0,30	1,90	294
VI	11,1	10,3	3,8	19,2	0,39	0,009	0,37	0,97	288
VII	10,6	6,6	21,1	43,4	0,93	0,064	0,63	1,63	419

The changes of mean water temperature along the Vistula river are quite similar during all three years. The average temperature at station No.1 was between 9,8 and 11,1 °C. The lowest temperature was observed in 1973. On the stretch upstream from the Kozienice power plant the temperature of the river water was slightly effected by the Radomka tributary, whose average water temperature was 4 to 6 °C, higher than the Vistula water temperature. The temperature of the Vistula water downstream from Kozienice is considerably influenced by discharge from the power plant and its average temperature was 20,8 - 22,8 °C. As the power production of the plant has increased in time, the difference between mean water temperature downstream and upstream from the heated waters discharge point has also increased. Thus in 1973 this difference amounted to 1,2 °C, in 1974 to 2,1 °C and in 1975 to 2,7 °C. It was also observed that the length of the river stretch influenced by heated waters has increased as well. Thus the water temperature has reached the natural temperature level at the distance of 30 km downstream from the discharge point in 1973, whereas in 1974 this distance equalled to 63 km. In 1975 it was observed that the minimal mean water temperature at all stretch downstream from the discharge point was 1 °C higher than mean temperature upstream from the discharge point.

The minimal and maximal water temperatures changed along the river course similarly to mean temperatures. The highest values of temperatures were observed at station 4 in 1974 and 1975 (fig.7).

The data concerning dissolved oxygen concentration show that the oxygen conditions in the whole river changed during the years. The lowest average dissolved oxygen concentrations were observed in 1973 (fig.8). At this time the DO balance was considerably effected by the waste water discharge through the Radomka river. The decrease of oxygen concentration below this tributary was higher than below the Kozienice power plant.

The best oxygen conditions in the Vistula river were observed in 1973. This is evident from the extreme values of oxygen concentrations as well:

	DO concentration mg/l	
	minimum	maximum
1973	6,3 - 7,9	11,8 - 16,8
1974	5,7 - 7,4	11,3 - 16,8
1975	6,0 - 8,2	12,0 - 16,4

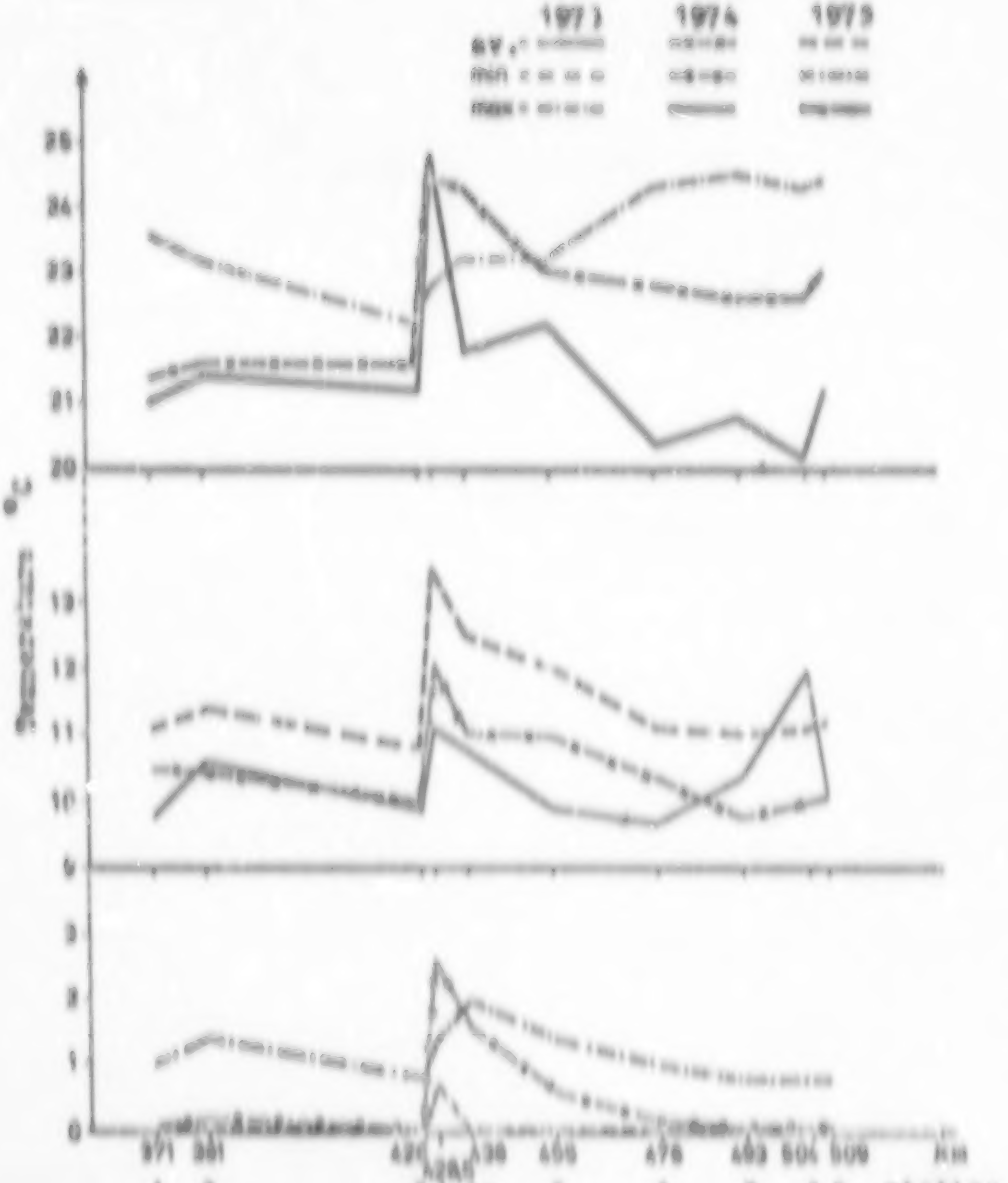


Fig. 7. Changes of yearly water temperature along Vistula river

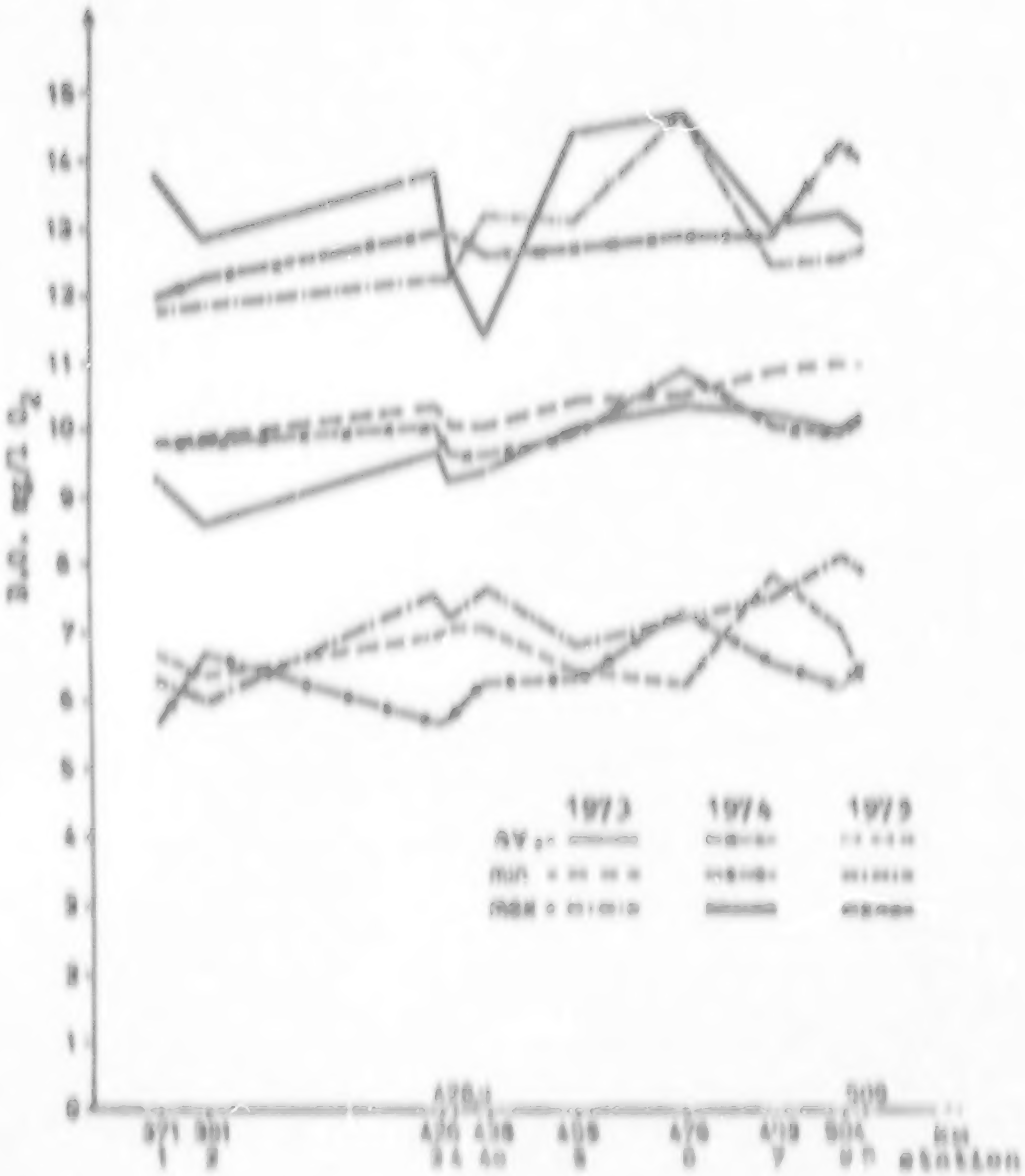


Fig. 8. Changes of yearly oxygen concentration along Vistula river

During all three years a similar decrease of average oxygen concentration below the Kozienice power plant was observed, (0,3 - 0,4 mg/l). This loss of oxygen was completed at the distance of about 30 km downstream from the heated waters discharge point.

It should be pointed out that during all three years the oxygen condition in the Vistula water was satisfactory. At all stations the phenomena of supersaturation could be observed, sometimes reaching 160 %.

From among the tributaries the water in Jeziorka contained the smallest amount of dissolved oxygen. Its mean concentration was from 6,6 - 7,7 mg/l O_2 and sometimes decreased below 2 mg/l O_2.

Such low oxygen concentration was observed in Wieprz and Zagożdżonka as well, but only in 1973.

Good oxygen conditions in the heated water discharged from the power plant should be noted. The oxygen concentration was within a scope of 6,6 - 11,5 mg/l O_2. The yearly mean values were above 8 mg/l O_2. Sometimes even supersaturation was observed.

The BOD_5 values of the Vistula river show that the concentration of easily decomposing organic matter was different in given years. The yearly mean BOD_5 show clearly that the highest pollution by organics was in 1973 and the lowest in 1975. The course of changes of mean values along the river was similar in all years (Fig. 9).
At the river stretch above the Kozienice power plant and downstream from the Kurówka river mouth a considerable BOD_5 increase was observed, the water of this tributary was very polluted by organics. Maximal value of its BOD_5 reached 30 mg/l O_2 in 1973.
Downstream from the heated waters discharge point (station 4) the yearly mean value of BOD_5 decreased in 1973 but it did not change in the next two years. At the Vistula stretch from Kozienice to Warsaw one could observe two points of considerable increase of organics concentration. One point was below the Radomka river mouth, which BOD_5 reached maximal values of 23 mg/l O_2 in 1975. The next important source of pollution was Jeziorka river, which BOD_5 reached 100 mg/l O_2.

The concentration of nitrogen compounds was considerable in the Vistula river over the period of observation. It concerned organic as well as inorganic compounds of nitrogen soluble in water.

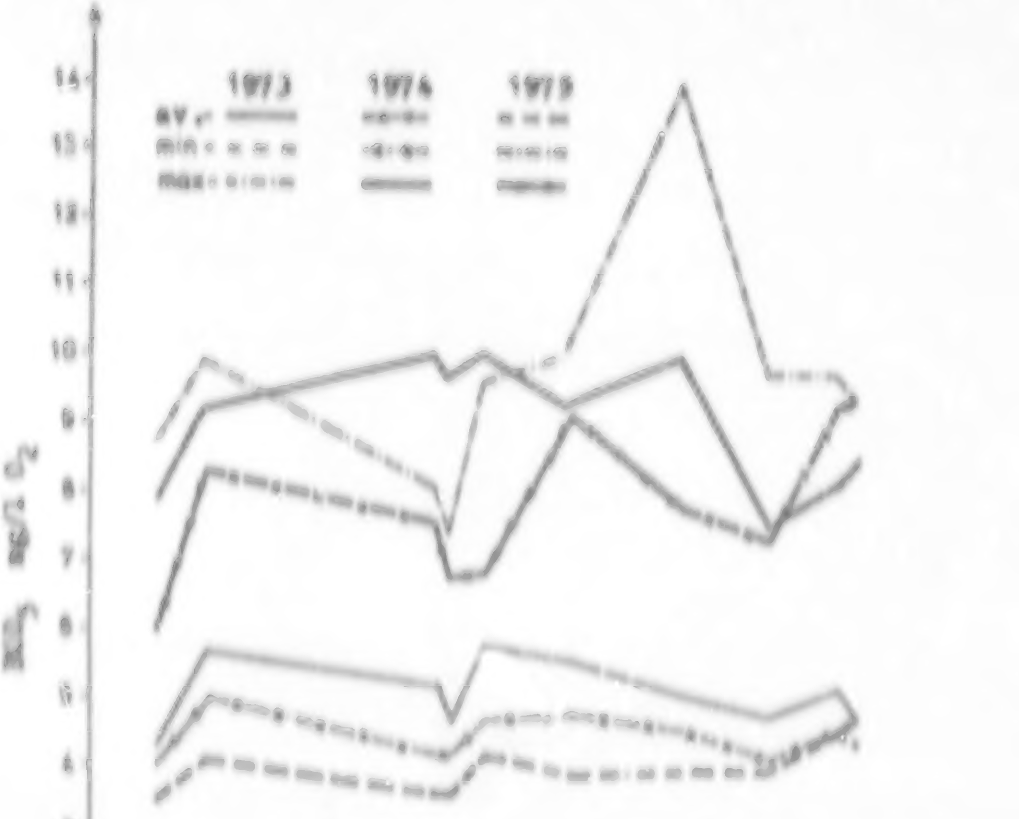


Fig.9. Changes of yearly BOD_5 along Vistula river

Among the inorganic compounds ammonia reached the highest level of concentration of nearly 5 mg/l N in 1973. The yearly mean concentration was different in given years. This proves that the pollution of the Vistula water by ammonia decreased from year to year. This could be observed along all investigated points of the river. The changes of ammonia concentration along the river were similar (fig.10). Distinct increase of ammonia concentration was always noticed at station 2 which shows that the main source of pollution by ammonia were the Nitrogen Fertilisers Works in Puławy. The waste waters from these works discharged into the Kurówka river, caused an increase of ammonia concentration in Kurówka water. Yearly mean values were between 12,7 - 15,4 mg/l N. The maximum value reached 23,6 mg/l N.

The concentration of nitrates in the Vistula water was also high. The average yearly concentration was relatively similar along the surveyed stretch of the Vistula during all periods of research. It ranged from 0.74 to 1,2 mg/l N.

The concentrations of nitrate in Vistula water were also distinctly affected by the wastes discharged from the Nitrogen Fertilisers Works into the Kurówka river. From among all investigated tributaries the Kurówka river was mostly polluted by nitrates. Its concentration ranged from 2,4 to 7,0 mg/l N. The yearly average values were between 4,1 and 4,9 mg/l N.

The concentration of nitrogen fixed in nitrite compounds was much lower than in the above mentioned compounds. The concentration range was between 0,002 to 0,156 mg/l N during all periods of research. The yearly average concentrations had similar range for all years and enclosed between 0,021 and 0,031 mg/l N.

The distribution of yearly average nitrite concentration along the surveyed stretch of the Vistula was similar in the successive years (fig.11). The concentration of nitrites was affected first of all by the Kurówka river. The concentration of nitrites in Kurówka water sometimes exceeded 1,00 mg/l N. The yearly mean values ranged from 0,416 to 0,451. Such polluted water caused almost double concentration of nitrite in the Vistula river at station 2. Downstream from this station we observed successive decrease of concentration of nitrite up to station 4. At station 6 the average annual concentration increased again. This phenomenon should be considered as the effect of the heated water discharged from the Kozienice power plant.

The concentration of organic compounds of nitrogen was comparatively high. The maximum yearly concentration during all periods of investigation reached 5,47 mg/l. The yearly average values show that the pollution of the Vistula water by nitrogen

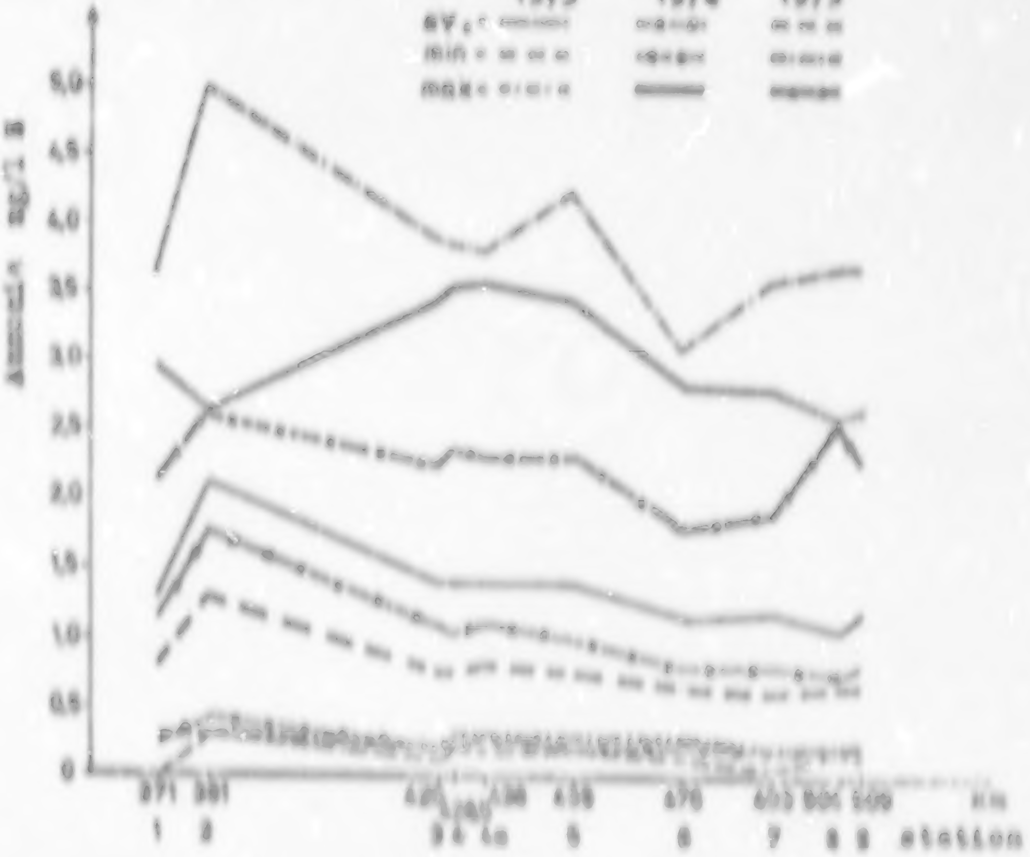


Fig. 10. Changes of yearly ammonia concentration along Vistula river

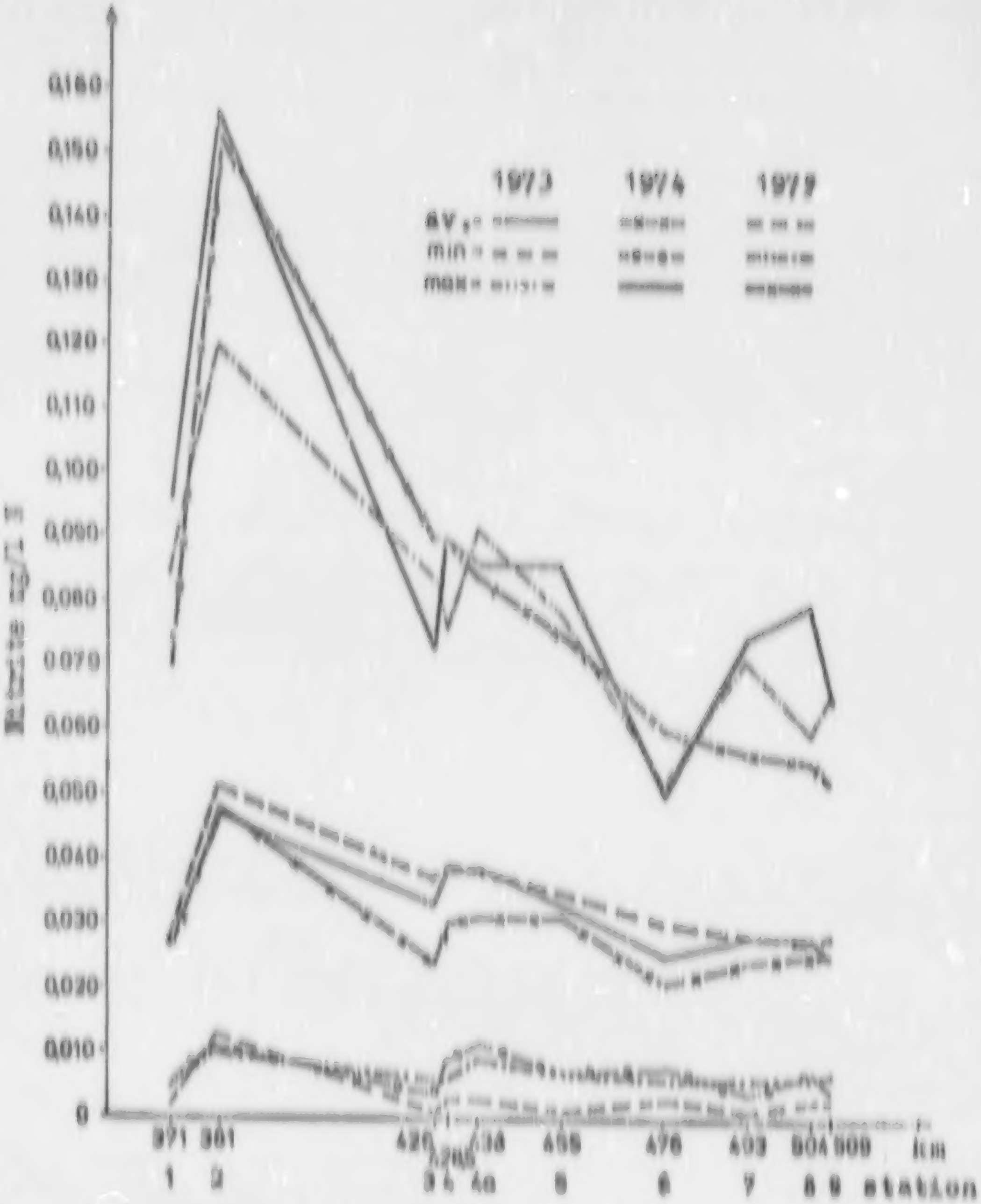


Fig. 11. Changes of yearly nitrite concentration along Vistula river

organic compounds decreased from 1973 to 1975. The changes of yearly average concentrations along the surveyed stretch of the Vistula demonstrated that the main source of nitrogen organic compounds was the Nitrogen Fertilizers Works (fig.12).

The above discussed data, as well as the yearly average results of turbidity, colour, conductance, residue and phosphate show that the water quality at Vistula section between Puławy and Warsaw was better in 1975. During this period we could observe a clearly polluting influence of the Vistula tributaries Kurówka, Radomka and Jeziorka.

The effect of heated waters discharge from the Kozienice power plant on the Vistula water quality -

The evaluation of the heated water influence on the Vistula water is based on comparing water quality observed upstream and downstream from the heated water discharge point.

The research on the influence of heated waters discharge from the Kozienice power plant was conducted during the first three years of the plant's work with a simultaneous and constant increase of the plant's capacity (fig.13).

In the first year of research the capacity of the plant equalled from 200 to 870 MW (tabl.24), with the exception of January when the power plant was not working. In the second year the lowest capacity during research was 560 MW, and the highest 1180 MW (tabl.25). During this period only three times did the power of the plant equal or exceed 1000 MW. In the third year, 1975, the capacity of the plant usually exceeded 1000 MW. The highest capacity during the time of research equalled 1960 MW (tabl.26).

The intensity of the discharging of the heated water from the power plant increased with the development of the plant's capacity (tabl.24,25,26). In the first year it equalled, on the days of research, from 4 to 23 m^3/s, in the second year from 13 to 46 m^3/s, and in the third from 19 to 58 m^3/s.

The flow in Vistula calculated on the basis of the flow rate for water gauge Dęblin (393.4 km) was usually typical. On the average, the river was most poor in water in 1973. The intensity of flow in 1973 was between 201 and 875 m^3/s (tabl.24) in 1974 from 260 to 1126 m^3/s, and in 1975 from 250 to 1160m^3/s (tabl.26).

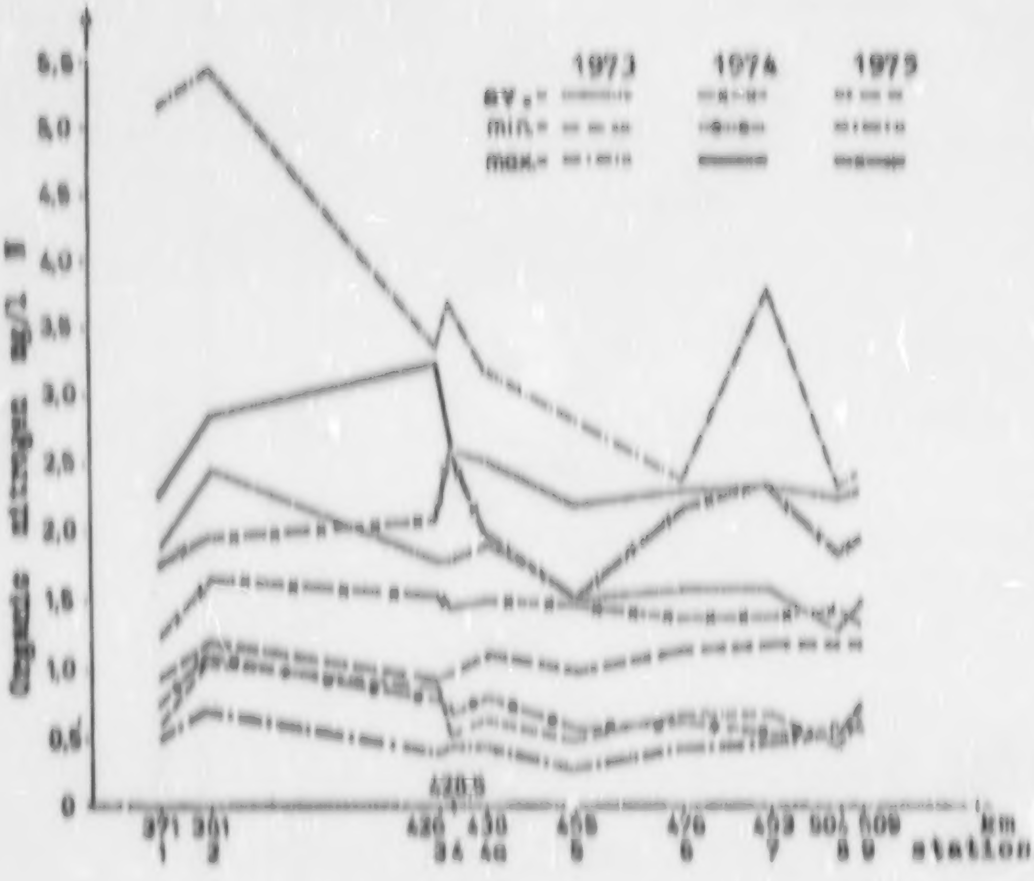


Fig. 12. Changes of yearly organic nitrogen concentration along Vistula river

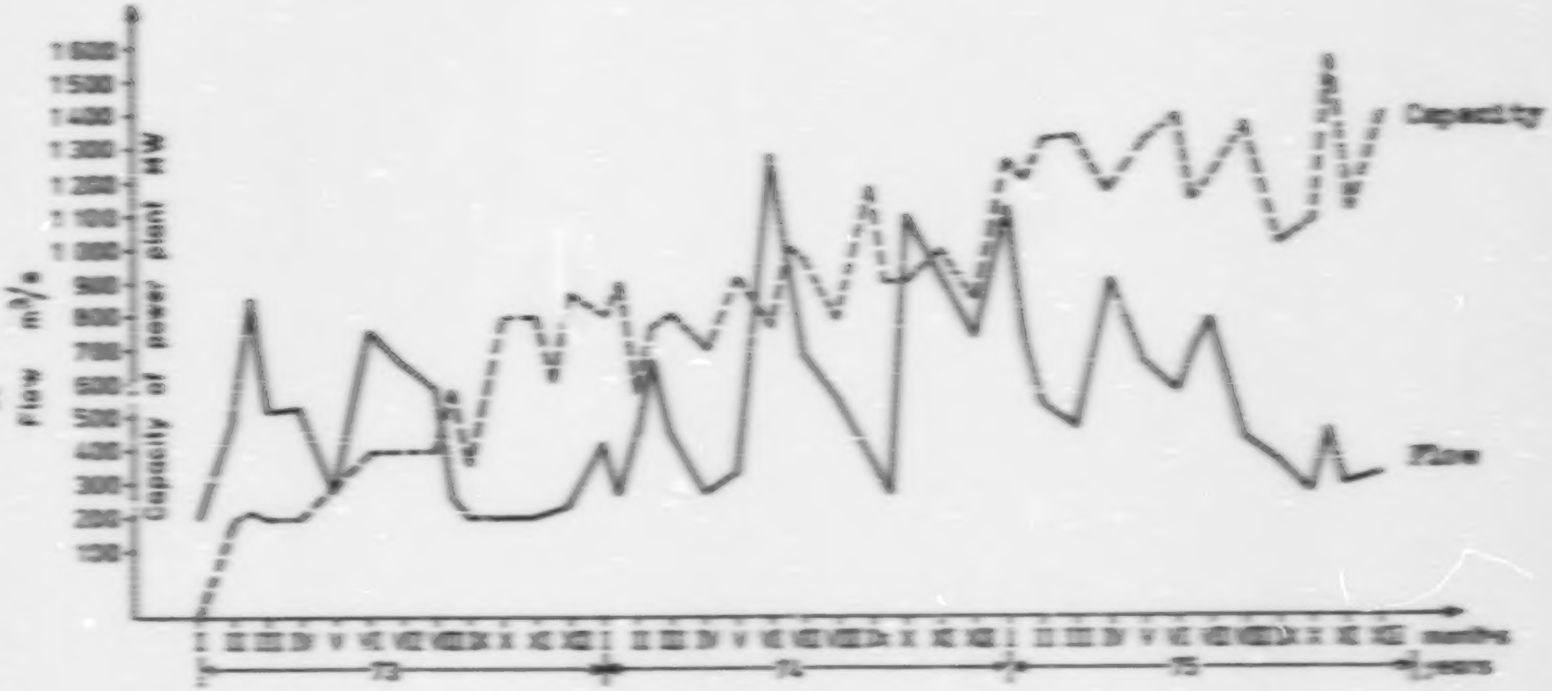


Fig.13. Flows of Vistula river and capacity of Kozienice power plant in days water quality measurement

Table 24. The capacity of power plant Kozienice (N), Vistula River flow above heated water discharge (Q) and in the discharge channel (Q_{IV}) during the time of water sampling 1973

Date	N MW	Q m^3/s	Q_{IV} m^3/s	$\frac{Q_{IV}}{Q}$ %
1.31	0	205	0	-
2.14	200	500	4.10	0.8
2.28	210	835	4.13	0.5
3.21	200	510	4.51	0.9
4.25	200	525	7.44	1.4
5.24	280	290	12.2	4.2
6.13	400	737	14.3	1.9
7.17	400	660	17.0	2.6
8.8	400	588	15.9	2.7
8.22	380	260	20.7	8.0
9.5	360	195	12.2	6.2
10.24	800	203	20.7	10.2
11.7	800	201	20.4	10.2
11.21	600	223	20.1	9.0
12.12	870	237	23.2	9.8

Table 25. The capacity of power plant Kozienice (N), Vistula River flow above heated water discharge (Q) and in the discharge channel (Q_{IV}) during the time of water sampling 1974

Date	N MW	Q m^3/s	Q_{IV} m^3/s	$\frac{Q_{IV}}{Q}$ %
1.3	800	420	20.0	4.8
1.16	900	270	24.3	9.0
2.6	560	450	14.3	3.2
2.21	760	672	16.6	2.5
3.6	800	450	13.0	2.9
4.3	700	284	26.0	9.1
5.7	920	335	26.6	7.9
6.5	760	1280	20.9	1.6
6.26	1000	970	25.8	2.6
7.10	970	690	28.3	4.1
8.7	780	536	24.5	4.6
9.4	1180	356	46.3	13.0
9.18	900	274	27.3	10.0
10.8	900	1100	37.0	3.4
11.14	1000	927	26.5	2.8
12.4	830	733	20.2	2.7

Table 26. The capacity of power plant Kozienice (N), Vistula River flow above heated water discharge (Q) and in the discharge channel (Q_{IV}) during the time of water sampling 1975

Date	N MW	Q m^3/s	Q_{IV} m^3/s	$\frac{Q_{IV}}{Q}$ %
1.7	1260	1120	25.8	2.3
1.21	1200	727	19.1	2.6
2.4	1320	538	25.9	4.8
3.11	1330	406	22.3	4.8
4.23	1170	914	44.0	4.8
5.13	1380	661	31.2	4.7
6.3	1400	576	31.7	5.5
6.17	1140	702	30.4	4.3
7.8	1200	788	44.2	5.6
8.19	1380	434	52.9	12.2
9.16	1020	370	42.7	11.5
10.7	1080	284	41.7	14.7
10.31	1560	466	58.3	12.5
11.14	1100	310	19.9	6.4
12.2	1400	329	26.9	8.2

In the first year of research the discharge of heated waters from the power plant Kozienice ranged from 0.9 to 10.2 % of the Vistula flow, in the second year from 2.9 to 13.0 %, and in the third from 2.3 to 4.7 % (tabl.24,25,26).

The temperature of the heated water discharged into the channel ranged from 13.2 to 30 °C during sampling time. The differences between temperature of heated water and sampled water ranged from 9 to 20 °C. The highest differences were observed in winter time (fig.14).

The heated water discharged into the Vistula river downstream from the power plant affected the temperature by increasing in from 0 °C to 6.0 °C in relation to the area upstream from the power plant. The highest difference appeared in December, 1975 (fig.15).

The concentration of dissolved oxygen in the Vistula river upstream from the power plant was always high. In the period of research the lowest oxygen concentration equalled 5.7 mg/l O_2. Sometimes supersaturation occurred and reached 142 %. After passing through the cooling system the concentration of oxygen decreased, but sometimes an increase was also noted (fig.14). On the basis of obtained results it could be stated that the higher the concentration of oxygen in inflowing water (station no.3) the larger the decrease of the oxygen concentration. This regularity as shown of fig.16,17 , was observed in all years.

Similar conclusions can be drawn by evaluating the differences between the oxygen concentrations by means of the statistical method.After passingthrough the cooling system the average decrease of the oxygen amount (Δ) equalled:

$$1973\ \Delta = 1.07 \pm 0.6\ \mathrm{mg/l}\ O_2$$
$$1974\ \Delta = 1.16 \pm 0.68\ \mathrm{mg/l}\ O_2$$
$$1975\ \Delta = 1.00 \pm 0.72\ \mathrm{mg/l}\ O_2$$

At the same time the percentage of the oxygen saturation increased, due to the increase in temperature. The observation of the changes in oxygen concentration in given years during the development of the plant did not show the existence of relations between the changes in oxygen concentration and the capacity of the power plant.

The differences in oxygen concentration downstream and upstream from the heated water discharge point were distinct but not very high. Usually a decrease of oxygen concentration could be observed, but sometimes also a slight increase was noticed.

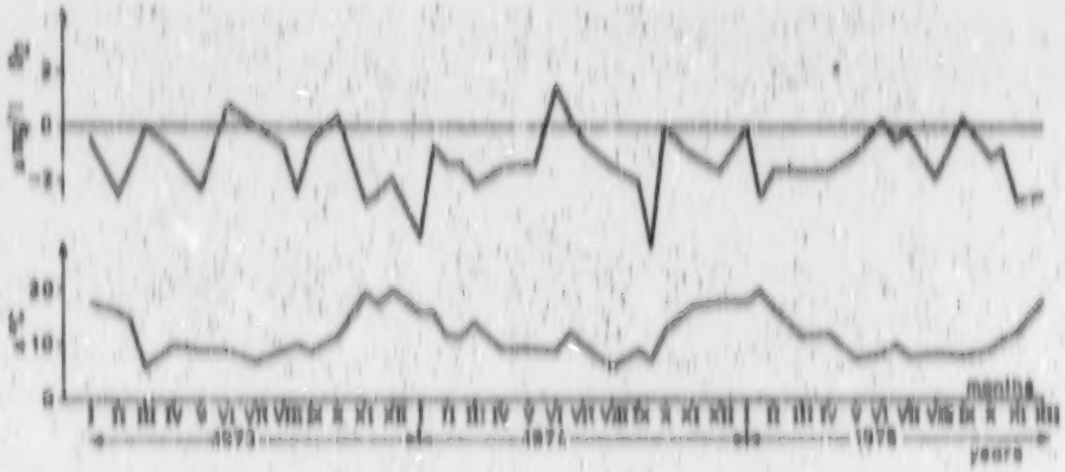


Fig. 14. The differences of water temperature and D.O. concentration between station No IV and No 3 left bank

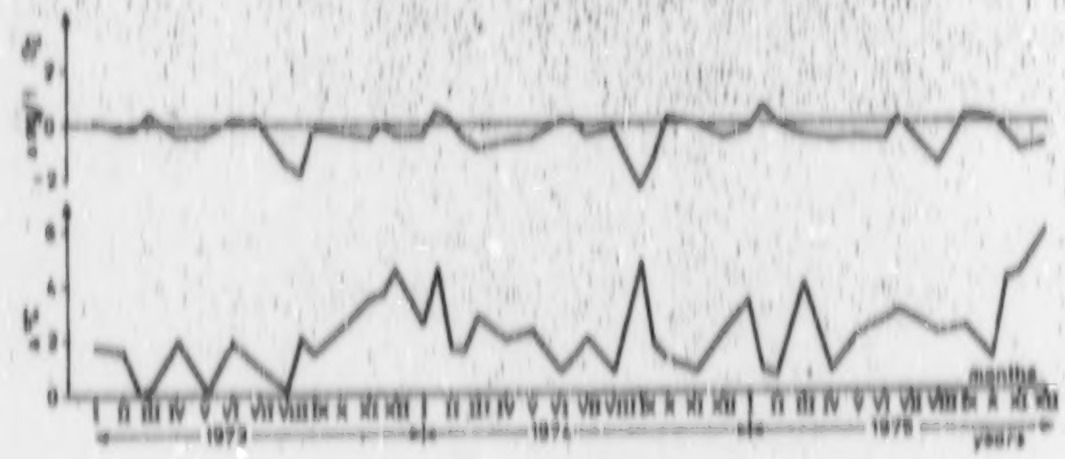


Fig. 15. The differences of water temperature and D.O. concentration between station No 4 and No 3 left bank

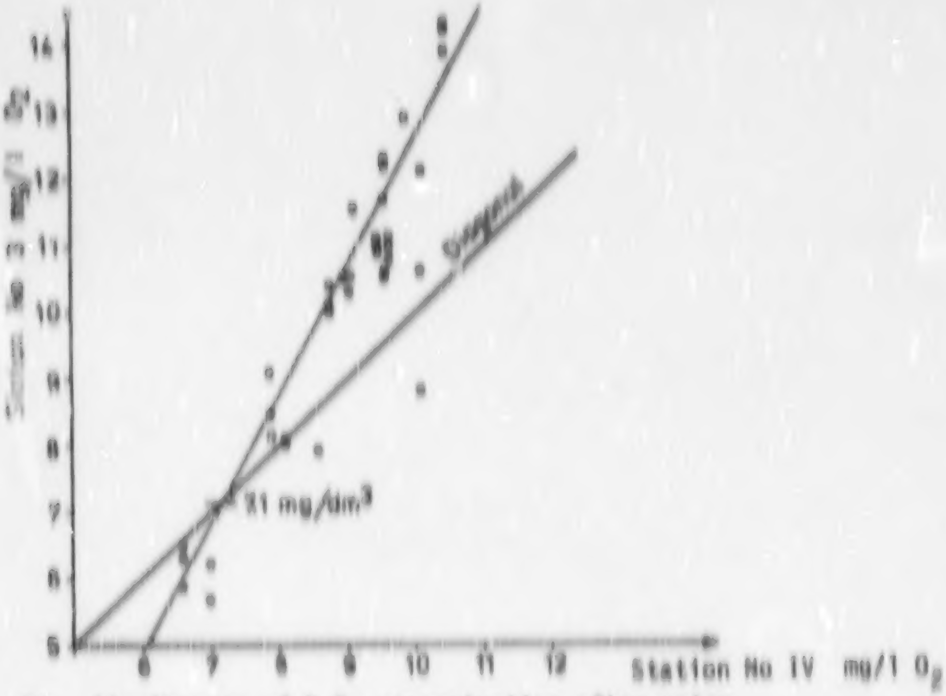


Fig. 16. Changes of D.O. concentration after water pass through cooling system, 1974

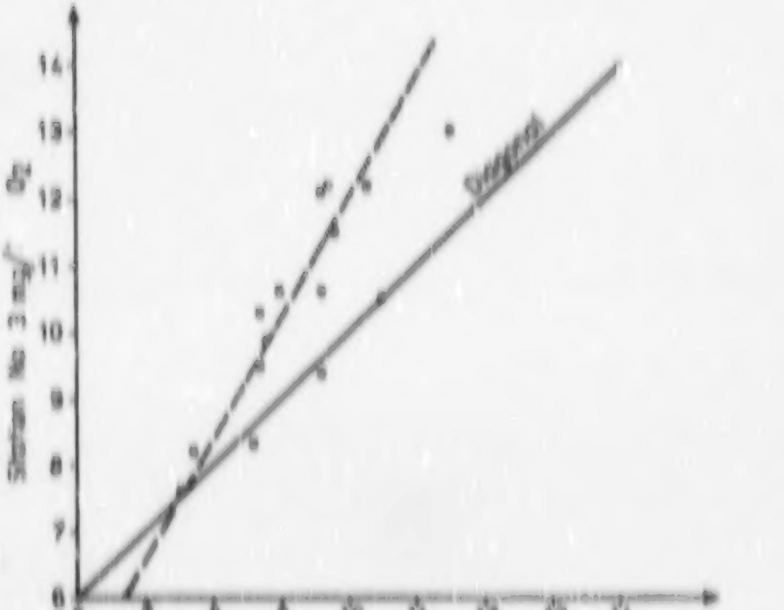


Fig. 17. Changes of D.O. concentration after water pass through cooling system, 1975

The maximal decrease of oxygen concentration at station no. 4 (left bank) reached 2.4 mg/l O_2. The average yearly decrease was very small and equalled:

1973 = 0.08 ± 0.20 mg/l O_2
1974 = 0.08 ± 0.17 mg/l O_2
1975 = 0.33 ± 0.28 mg/l O_2

Biochemical oxygen demand of Vistula water above the Kozienice power plant station no.3, left bank ranged from 0.7 mg/l O_2 to 10.0 mg/l O_2. The highest BOD_5 was noted in May (1973 and 1974) and in August (1975). The maximal values for subsequent years equalled 8.1; 10.0; 7.6 mg/l O_2.

The changes of the BOD_5 of water after passing through the cooling system varied (fig. 18,19). The BOD_5 differences intake water and discharged heated water ranged from minus 2 mg/l O_2 to plus 4.4 mg/l O_2.

The BOD_5 of Vistula water below the heated water discharge point was from 1.1 to 9.7 mg/l O_2. In general, the changes of BOD_5 during all years were similar to those observed upstream from the power plant. The differences between BOD_5 at station no. 4 and no. 3 (left bank) ranged from minus 2.4 to plus 2.1 mg/l O_2.

The ammonia concentration of Vistula water above the Kozienice power plant was rather high. It ranged from 0.17 to 3.92 mg/l N at the left bank. The same range of ammonia concentration as in the heated water was observed in the Vistula water below the power plant. The comparison of ammonia concentration at station no.3 and no IVis shown in fig.20.

It should be noted that the concentration of ammonia in the Vistula water was very changeable, depending on the season (fig. 21). The lowest concentration occurred in summer and the highest in winter in the period of low water temperature. Especially high concentrations occurred during the period when the surface water of Vistula was frozen. When concentration of ammonia was low, the heating of water has not caused any increase. At the same time one could observe that at ammonia concentrations higher than 2 mg/l N the ammonia concentration downstream from the power plant decreased.

The concentration of nitrites in the Vistula water above the power plant was low, with minimal values equalling in the period of research to 0.001 mg/l N and maximal values to 0.090 mg/l N. In water discharged from the cooling system of the plant and in the Vistula water below the plant it was possible to

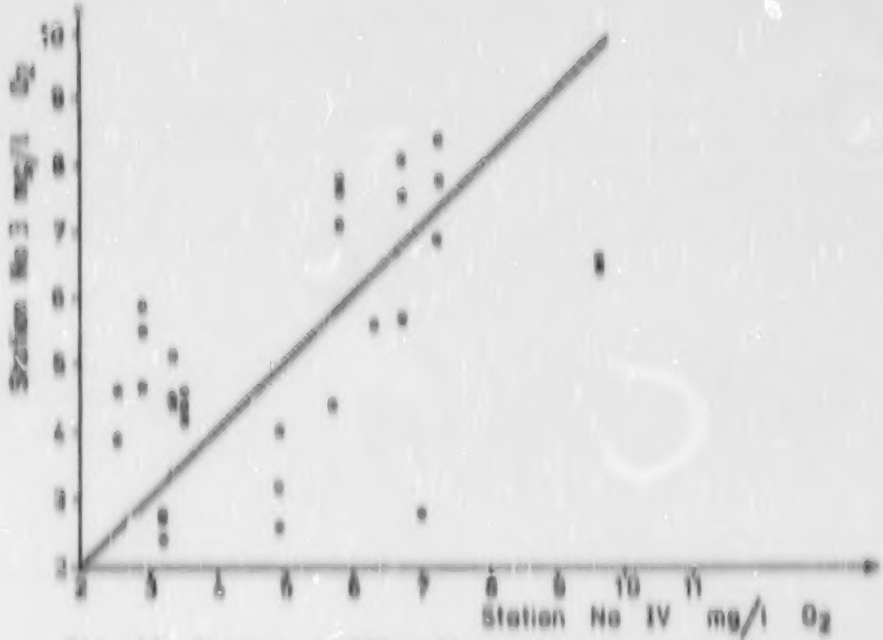


Fig. 18. Changes of BOD$_5$ after water pass through cooling system; 1975

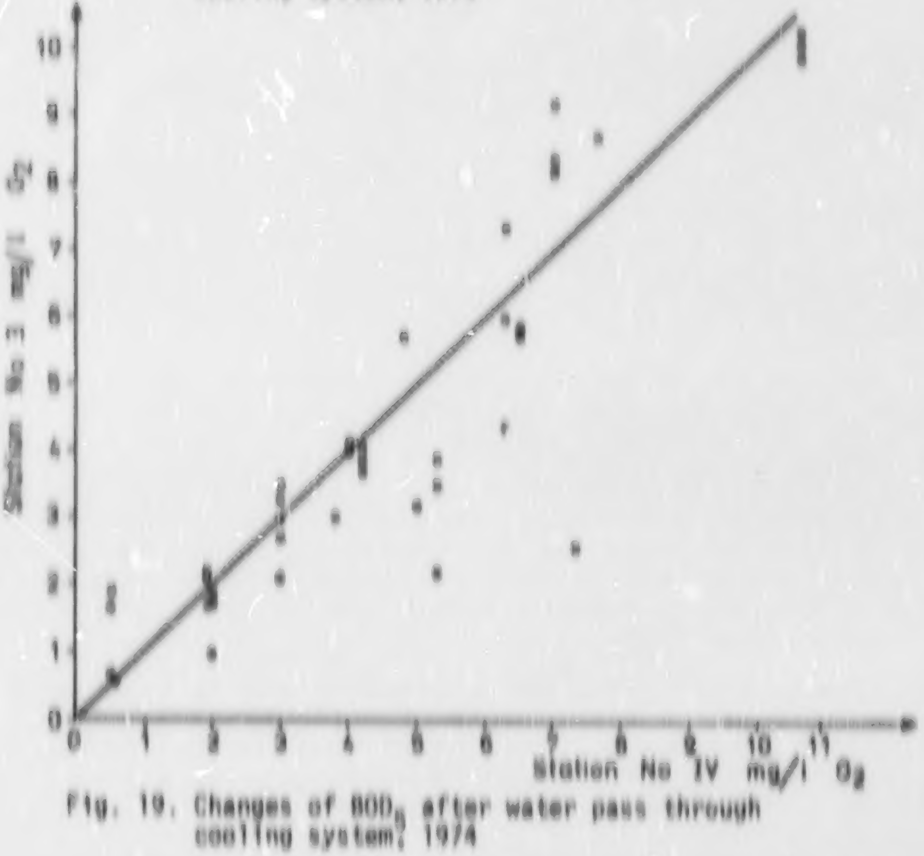


Fig. 19. Changes of BOD$_5$ after water pass through cooling system; 1974

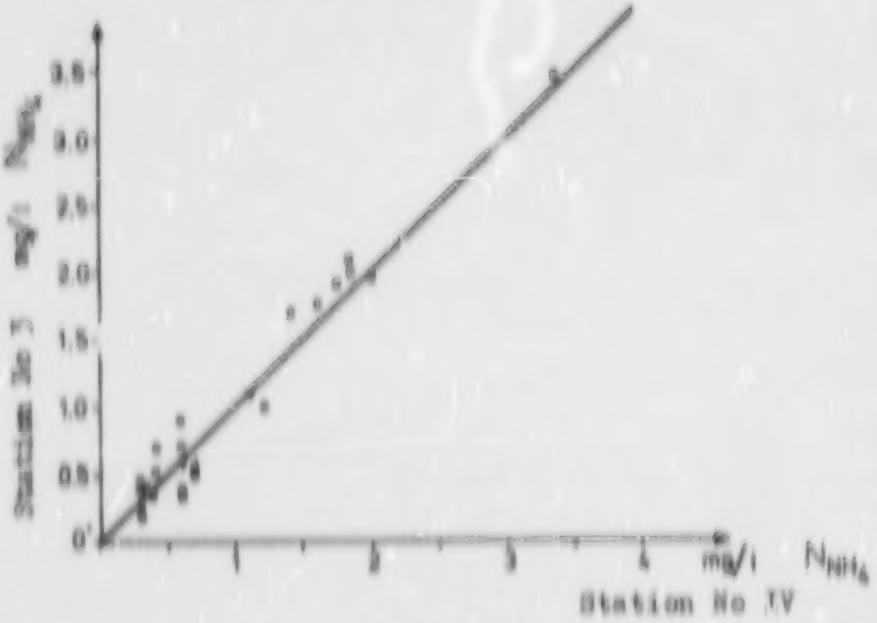


Fig.20. Changes of ammonia concentration after water pass through cooling system 1974

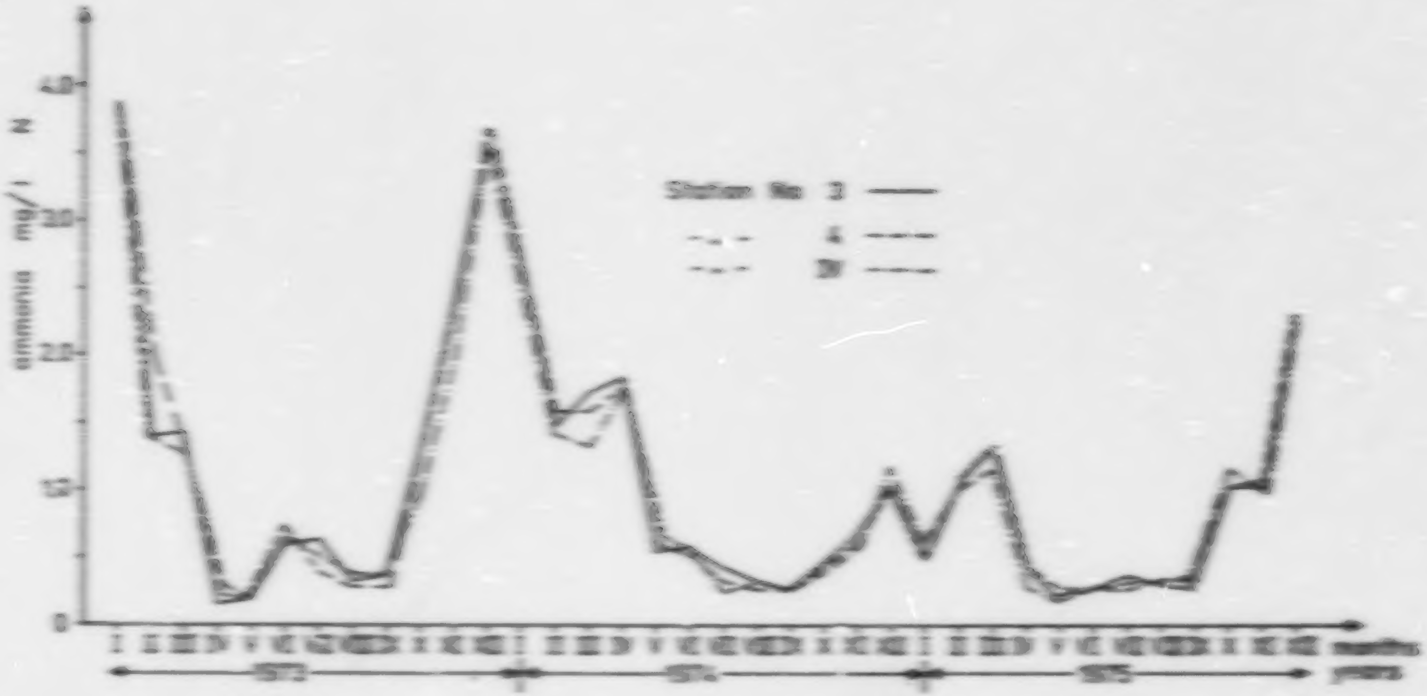


Fig. 27. Monthly changes of ammonia concentration of Vistula River around Kozienice

observe an increase of concentration of nitrites (fig.22), which ranged from 0,002 to 0,134 mg/l N. The differences between stations No.3 and No.4 ranged from minus 0,014 to plus 0,098 mg/l N.

Downstream from the heated water discharge point the nitrite concentration ranged from 0,003 to 0,090 mg/l N. The differences in relation to station 3 were not so high and equalled from minus 0,028 to plus 0,042 mg/l N.

Other parameters of the water quality like color, turbidity, odor, pH, COD, nitrates, organic nitrogen, dry residue, phenols and conductance did not undergo any visible changes under the influence of heated waters.

The evaluation of the influence of thermal water discharge on the quality of Vistula water based on the frequency of occurance of the negative and positive differences of some parameters between stations No. 4 and No. 3 (tabl.27).

We can see that only some parameters show the tendency of change the water quality. In most cases the water heating caused a decrease of DO concentration and an increase of nitrite concentration. But the decrease of D.O. concentration was not large in comparison with the water temperature increase, so the water saturation increased sometimes in areas downstream from the power plant. The BOD_5 shows some tendency to decrease after passing the cooling system. For other parameters the changes are not one-directional, but it could be stated that they don't demonstrate the deterioration the Vistula water quality downstream from the thermal water discharge point.

The hydrothermal study showed the temperature stratification in the cross-section of the river. That is why the comparison of the water quality at the left and right river bank may give some information useful for the evaluation of the influence of thermal water discharge on the water quality. Frequency of occurance of the negative and positive differences between station 4 l and 4 r is shown below on tabl. 28.

From this table we can see that similarly to the comparison of stations No.4 l and 3 l, the decrease of D.O. concentration in water of higher temperature was noticed. And in this case not every time the decrease of D.O. concentration caused the decrease of D.O. saturation. The increase of nitrite concentration in the heated stream was very clearly determined in 1975 when the temperature difference was higher. Some decrease tendency of organic nitrogen in the heated stream could be noticed every year. The frequency of decrease was higher from year to year, depending on the development of the power plant.

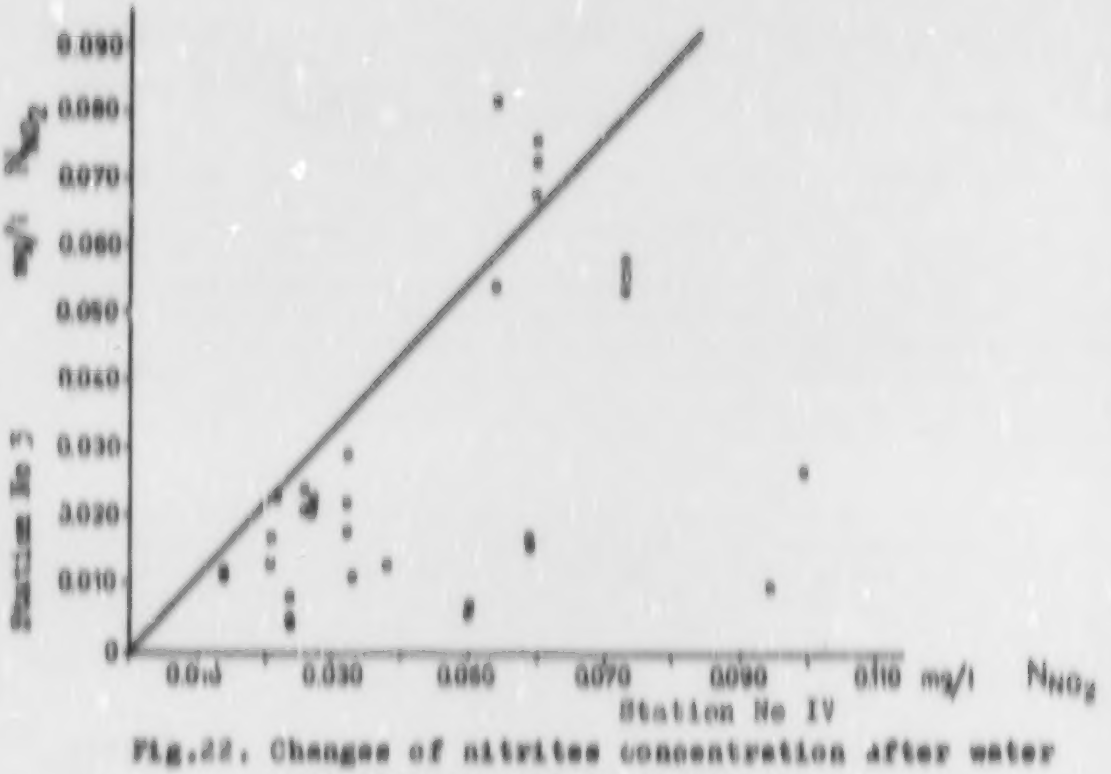


Fig.22. Changes of nitrites concentration after water pass through cooling system

Table 27. Frequency of negative and positive changes of water quality parameters upstream and downstream from the power plant (stations No. 4 1 - 3 1)

	D.O		D.O.%		BOD_5		COD		N_3		N_2		N_3		$P_{tot.}$	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1973 n=15	4	10	9	6	6	9	5	9	7	7	7	4	7	8	8	7
1974 n=16	5	10	6	7	8	8	5	10	7	8	12	3	3	11	6	10
1975 n=15	4	9	10	3	6	8	7	4	7	5	8	5	9	6	7	8

where n-the number of measurements

Table 28. Frequency of negative and positive differences of the water quality parameters at the left and right river bank of the Vistula river (stations 4 l - 4 r)

	D.O		D.O. %		BOD_5		COD		N_3		N_2		N_3		$N_{org.}$	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1973 n=10	0	9	3	5	2	7	3	7	2	7	4	6	6	4	4	5
1974 n=12	3	9	5	7	4	8	5	7	5	6	6	5	7	4	5	7
1975 n=13	3	8	10	2	7	5	6	6	4	5	8	2	8	4	5	8

The same can be noted with nitrite concentration at the left bank of the river.

In order to draw a more reliable conclusion on the effect of the Kozienice power plant on the Vistula water quality we took under the consideration the results of observation made during the critical periods i.e. of high power production, low river flow and high natural water temperature. Such situation occurred every year in August (tabl. 29).

These observations show a large D.O. concentration decrease at station 4. The most evident decrease (1.9 mg/l) was observed in August, 1973. At that time the natural temperature was lowest in relation to other years and the temperature increase downstream from the power plant equalled 2.1 °C. In 1974, when the natural water temperature was highest and the temperature increase lowest (0.8 °C), the D.O. concentration decrease was hardly observable.

The BOD$_5$ changes were similar. The decrease of BOD$_5$ was influenced by parameters in the same way as D.O. Thus, the BOD$_5$ decrease amounted to 1.7 mg/l in 1973 and to 0.3 mg/l in 1974.

The nitrite concentration upstream from the power plant Kozienice was in this case similar. Downstream from the power plant it changed twice in plus and once in minus. The increase of nitrite concentration was observed when a higher temperature increase occurred.

The other tested water quality parameters such as ammonia, nitrate and organic nitrogen did not show any significant changes caused by the heated water discharge from the power plant.

Summarizing, it can be ascertained that the effect of the Kozienice power plant discharge on the water quality of the receiver is limited even during the critical period of the year, to a little D.O. concentration decrease and a nitrite concentration increase. The same is demonstrated by the results of twenty-four hour investigation carried out in April, 1975 at stations no.3 l, 4 l, IV and IVa (fig.23). (Enclosure 100).

The flow of water in the Vistula in that period was high: 1470 - 1590 m^3/s. The capacity of the power plant equalled from 1200 to 1600 MW (fig.24).

The range and average results of the twenty-four hour physical and chemical investigation are shown in the tabl. 30.

Table 29. The results of Vistula water investigation close Kozienice power plant during the critical periods

Station No	Parameters	8.22.73	8.7. 74	8.19.75
	Capacity MW	980	780	1380
	Flow Q m^3/s	285	467	391
3	Temperature: °C	18.7	21.2	20.4
4	Temperature: °C	20.8	22.0	22.6
3	D.O. mg/l O_2	9.9	10.5	1[illegible].2
4	D.O. mg/l O_2	8.0	10.3	10.8
3	BOD_5 mg/l O_2	8.1	5.7	7.6
4	BOD_5 mg/l O_2	6.4	5.4	6.8
3	NO_2 mg/l N	0.029	0.023	0.029
4	NO_2 mg/l N	0.037	0.016	0.027
3	NO_3 mg/l N	0.77	0.92	0.93
4	NO_3 mg/l N	0.87	0.90	1.02
3	NH_3 mg/l N	0.34	0.33	0.36
4	NH_3 mg/l N	0.42	0.31	0.34
3	$N_{org.}$ mg/l N	1.39	1.73	1.46
4	$N_{org.}$ mg/l N	1.42	1.43	1.42
3	COD mg/l O_2	26.9	25.2	30.9
4	COD mg/l O_2	27.0	23.0	26.6

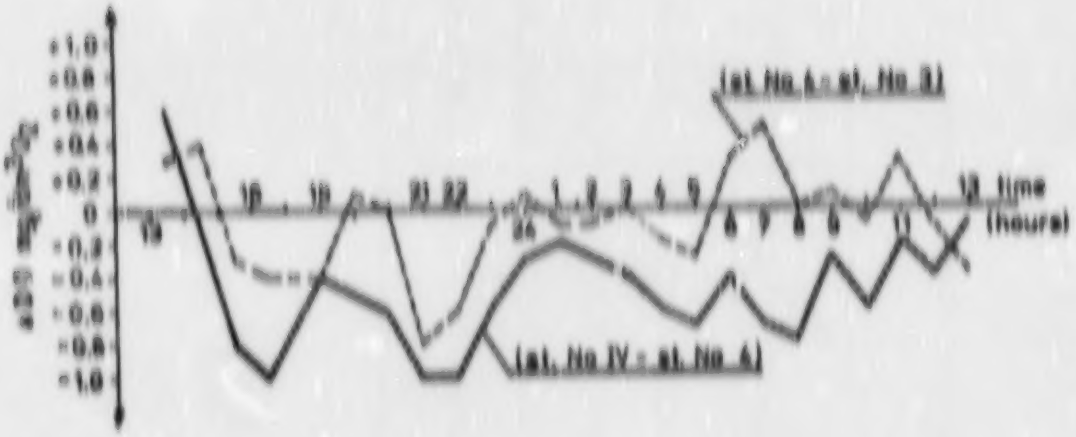


Fig.23. Changes of D.O. concentration in heated water channel and in Vistula water downstream of Kozienice Power plant, April 15-16, 1979

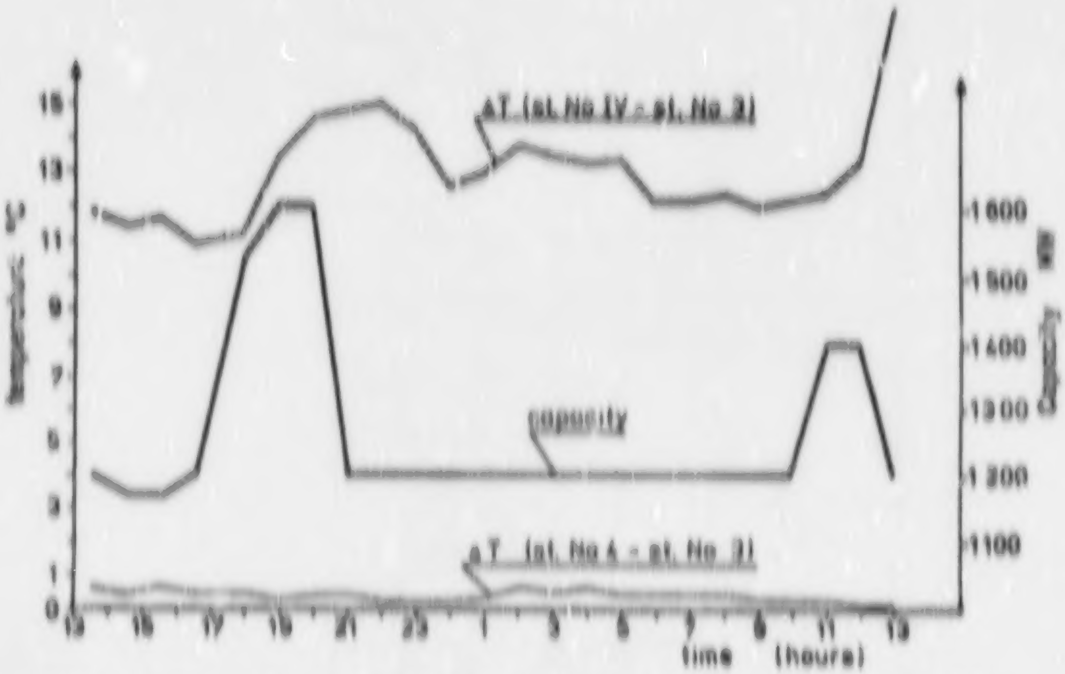


Fig.24. Changes of Kozienice Power plant capacity and increases of water temperature in April, 15-16, 1976

Table 30. Range and average results of twenty-four hours investigation of Vistula river
April 15-16, 1959

Station	Temp. of water °C			D.O mg/l			D.O %			BOD_5 mg/l			NO_2 mg/l			NO_3 mg/l		
No	min	max	aver	min	max	aver	min	max	aver	min	max	aver	min	max	aver	min	max	aver
3	6.0	7.0	6.5	9.4	10.3	10.0	77	85	81	1.9	5.3	3.2	0.002	0.017	0.008	0.16	0.64	0.46
IV	17.6	24.0	19.5	8.8	10.2	9.5	94	119	102	1.5	5.0	2.8	0.002	0.022	0.011	0.25	0.64	0.42
IVA	15.6	22.2	18.5	8.6	10.1	9.5	89	105	100	1.6	5.4	2.8	0.005	0.022	0.011	0.16	0.76	0.46
4	6.6	7.4	6.9	9.2	10.4	9.9	75	85	81	2.1	5.8	3.4	0.002	0.013	0.009	0.25	0.86	0.46

As it should be expected, the largest difference of the temperature was between heated water in channel (station no.IV) and Vistula water upstream from the power plant (station I). On the average it equalled to 13.0 °C. The largest differences of average results of chemical determination were also between the same two stations. Some decrease of D.O. was observed, as well as of BOD_5, NH_4, concentrations, and an increase of NO_3 concentration in the heated water.

The high level of the Vistula water flow during the investigation caused a very small increase of water temperature downstream from the water discharge point, in spite of high capacity of the power plant. Thus, a decrease of oxygen concentration in the Vistula river downstream from the power plant was low. The differences between other parameters were also not essential.

Mathematical Model of Water Quality Changes under the Influence of Thermal Water Discharge

Introduction

The main purpose of this discussion is to find the basic relations between heated waters discharge and the change of the water quality at the longitudinal and cross-sections downstream from the power plant Kozienice. Two mathematical models were proposed. The first is shown below in a general form:

$$y_i = f_i(x_1, x_2, x_3) \qquad (1)$$

where: y_i = δC_i concentration difference of the i-th substance between the stations upstream and downstream from the power plant, or = C_i concentration difference of the i-th substance between the left and right river bank downstream from the discharge point,

i = 1,2, ... 6

x_1 = q/Q the ratio of heated waters discharge to the flow rate in the vicinity of the power plant,

x_2 = ΔT_i = an increase of the water temperature below the power plant in relation to the waters upstream from the power plant

x_3 = T_j = water temperature upstream from the power plant.

After thoroughly analyzing the parameters influencing the change of water quality, it was decided to examine another model characterised by the following parameters:

$$y_i = f_i(x_1, x_2, x_3, x_4) \qquad (2)$$

where: x_1, x_2, x_3 as above

x_4 = $\bar{C}_{ji}$ = average concentration of the i-th substance upstream, or

x_4 = $Q \cdot C_{ji}$ load of the i-th substance upstream from the power plant.

The work has been divided into two parts. The first was devoted to an attempt at defining the character of functions 1 and 2 for each of the six water quality parameters. The second dealt with the approximation of functions for three and four variables.

The realization of the first group of tests was based on computer programs prepared in FORTRAN : APROX = 3, FUNCT = 3.

Input data. The input data have been obtained from the measurements at two cross-sections of Vistula, upstream and downstream from the power plant. At three points of each cross-section the following parameters were measured: BOD_5, dissolved oxygen, ammonia, nitrates, nitrites and organic nitrogen, as well as water temperature. There were six measurements. The flow rate was calculated by means of rating curves. The data showing the capacity of the power plant and the rate of the thermal water discharge during the days of the water quality testing were collected as well.

Preliminary assumptions. It has been determined that the stream of heated water reaches the area downstream from the power plant at the left river bank. Therefore, it was assumed that an essential influence of the temperature on the change of the water quality parameters can occur only at the left river bank. An already calculated measurement was adopted as an average concentration value at the cross-section in all cases when the remaining two measurments were missing. It has been decided that the final form of functions (1) and (2) will be as follows:

$$\Delta C_i = f_{1i}(q/Q) + f_{2i}(\Delta T_4) + f_{3i}(T_3) \qquad (1a)$$

$$\delta C_i = g_{1i}(q/Q) + g_{2i}(\Delta T_4) + g_{3i}(T_3) \qquad (1b)$$

and;

$$\Delta C_i = f_{1i}(q/Q) + f_{2i}(\Delta T_4) + f_{3i}(T_3) + f_{4i}(X_4) \qquad (2a)$$

$$\delta C_i = g_{1i}(q/Q) + g_{2i}(\Delta T_4) + g_{3i}(T_3) + g_{4i}(X_4) \qquad (2b)$$

The character of the partial functions f_{ij} and g_{ij} was determined on the basis of analyzed relations between ΔC_i or δC_i and each of the independent variables.

The calculation procedure

Relation between the concentration change at the cross-sectional areas downstream and upstream from the power plant Kozienice and the factors characterizing the influence of the heated waters discharge. This problem was solved in three stages.

1. Selection of factors which have an essential effect on the change of water quality. It was determined that the following factors influence the water quality downstream from the power

plant: capacity (N) of the power plant, flow rate (Q), the rate (q) of the heated water discharge, temperature (T_3) in the cross sectional area upstream and the temperature (T_4) downstream from the power plant. The computer program *FUNCT - 3* was used in approximating the following relations:

$$\delta C_i, \Delta C_i = f_i (N) \qquad (3)$$

$$\delta C_i, \Delta C_i = f_i (Q) \qquad (4)$$

$$\delta C_i, \Delta C_i = f_i (T_3) \qquad (5)$$

$$\delta C_i, \Delta C_i = f_i (T_4) \qquad (6)$$

$$\delta C_i, \Delta C_i = f_i (\Delta T_4) \qquad (7)$$

$$\delta C_i, \Delta C_i = f_i (q/Q) \qquad (8)$$

For the determination of the character of partial function the procedure *FUNCT - 3* was used, which for each relation (3) - (8) evaluates seven basic functions:

$$y = ax + b \qquad (9)$$

$$y = a/x + b \qquad (10)$$

$$y = 1/(ax+b) \qquad (11)$$

$$y = x/(ax+b) \qquad (12)$$

$$y = a \log(x) + b \qquad (13)$$

$$y = bx^a \qquad (14)$$

$$y = b \exp(ax) \qquad (15)$$

2. Then an appropriate type of partial function is chosen. For each function (9) - (15) an approximation of relations between water quality parameters and factors characterising the influence of thermal water discharge (3) - (8) is made. The coefficients of regression and linear correlation were calculated. The analysis of correlation coefficients allowed for the choice of the most proper function. The correlation coefficients and coefficients of linear regression were calculated with the help of the *FUNCT - 3* program.

The algorithm of that program is as follows:

a Choice of function character – in this case one of the seven functions (9) – (15)

b Conducting the function to a general linear form: if the general form of the relation can be:

$$Y = AX + B$$

then for *y*:

$y = a/x + b$; $Y = y$; $X = 1/x$; $A = a$; $B = b$
$y = 1/(ax+b)$; $Y = 1/y$; $X = x$; $A = a$; $B = b$
$y = x/(ax+b)$; $Y = 1/y$; $X = 1/x$; $A = b$; $B = a$
$y = a\log(x+b)$; $Y = y$; $X = \log x$; $A = a$; $B = b$
$y = bx^a$; $Y = \log y$; $X = \log x$; $A = a$; $B = \log b$
$y = b\exp(ax)$; $Y = \ln y$; $X = x$; $A = a$; $B = \ln b$

c Calculation of regression coefficients for each of functions (9) – (15):

$$A = \frac{\sum_{i}^{NPOM}(X_i - \bar{X})\cdot(Y_i - \bar{Y})}{\sum_{i}^{NPOM}(X_i - \bar{X})^2} \tag{16}$$

$$B = \bar{Y} - A\bar{X} \tag{17}$$

and linear correlation coefficients:

$$\varrho_{Kl} = \frac{\sum_{i}^{NPOM}(X_i - \bar{X})\cdot(Y_i - \bar{Y})}{\sqrt{\sum_{i}^{NPOM}(X_i - \bar{X})^2}\cdot\sqrt{\sum^{NPOM}(Y_i - \bar{Y})^2}} \tag{18}$$

where:

$\bar{X}$ = average value of the transformed independent variables,

$\bar{Y}$ = average value of the dependent variables,

NPOM = number of measurements,

K, 1,2,3 .... 6 - the number of variable according to functions (3 - 8)

l, 1,2,3 .... 7 - the number of regression function (9 - 15)

The calculated correlation coefficients have been presented as follows:

$$(\rho_{Kl}) = \begin{Bmatrix} \rho_{11}, \rho_{12}, \cdots\cdots\cdots \rho_{17} \\ \rho_{21}, \rho_{22}, \cdots\cdots\cdots \rho_{27} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \rho_{61}, \rho_{62}, \cdots\cdots\cdots \rho_{67} \end{Bmatrix} \Longrightarrow \begin{Bmatrix} \rho_1 \max \\ \rho_2 \max \\ \rho_3 \max \\ \rho_4 \max \\ \rho_5 \max \\ \rho_6 \max \end{Bmatrix}$$

The choice of appropriate partial functions was based on finding in a given row of the (ρ_{Kl}) matrix a maximal value of correlation coefficient. The number of index corresponds to the number of assumed function (9)-(15). Because of very small differences (3)-(8) between the correlation coefficients for linear function ρ_{K1} and all the remaining coefficients, it was finally decided that partial functions are of linear character. The determination of which relations (3)-(8) will be included in the first model and which in the second was done by comparing maximal correlation coefficients and by choosing the three largest consecutive coefficients. This condition was met by the following functions:

$$f_l(q/Q),\ f_l(\Delta T_4),\ f_l(T_3)$$

The following final form was thus proposed for model 1:

$$y_l = a_{0l} + a_{1l}q/Q + a_{2l}\Delta T_4 + a_{3l}T_3 \qquad (19)$$

and for model 2:

$$y_l = b_{0l} + b_{1l}q/Q + b_{2l}\Delta T_4 + b_{3l}T_3 + b_{4l}x_4 \qquad (20)$$

The calculation of coefficients of regression surface for functions of many variables –

Approximations of the functions indicated by the formula (19) and (20) are obtained by the help of the APROX-3 computer program. The algorithm of this program is as follows:

1) Calculation of terms of correlation matrix

$$\Pi = (\varrho_{ik}) \tag{21}$$

where:

correlation coefficient ϱ_{ik} is calculated from the formula:

$$\varrho_{ik} = \frac{\sum_{K}^{NPOM} (x_{ki} - \bar{x}_i) \cdot (x_{kj} - \bar{x}_j)}{NPOM \cdot \delta(x_i) \cdot \delta(x_j)} \tag{22}$$

2) The formulation on the basis of correlation matrix and average deviation of the variance-covariance matrix

$$\gamma\delta\delta = \begin{Bmatrix} \sigma_1^2, & \varrho_{12}\,\sigma_1\,\sigma_2, & \dots\dots\dots\dots, & \varrho_{1j}\sigma_1\,\sigma_j \\ \varrho_{21}\,\sigma_2\,\sigma_1, & \sigma_2^2, & \dots\dots\dots\dots, & \varrho_{2j}\sigma_2\,\sigma_j \\ \dots\dots & \dots\dots & \dots\dots\dots\dots & \dots\dots \\ \dots\dots & \dots\dots & \dots\dots\dots\dots & \dots\dots \\ \varrho_{j1}\,\sigma_j\sigma_1, & \varrho_{j2}\,\sigma_j\sigma_2, & \dots\dots\dots\dots, & \sigma_j^2 \end{Bmatrix} \tag{23}$$

where:

$$\sigma_i = \sqrt{\frac{\sum_{K}^{NPOM} (x_{ik} - \bar{x}_i)^2}{NPOM}} \tag{24}$$

3) Coeffiuients of regression are calculated

$$b_{in} = \frac{\Theta_{ij}}{\Theta_{jj}} \tag{25}$$

$$b_{on} = \mu_g \cdot \sum_{i=1}^{l} b_i/\mu_i \tag{26}$$

where: Θ_{ij} - minor value of the matrix $\overline{\Theta\Theta}$

μ_g - average value

$i = 1,2,3$ or $i = 1,2, \ldots\ldots 4$

n - the number of a consecutive parameter of water quality

The determination of relation between the increase of concentration at cross-section –

The general form of this relation has been formulated above (19) and (20). The algorithm of calculations is shown in point 2, and calculations were realised with the help of the APROX-3 and FUNCT-3 computer programs. The value σC_i is calculated from:

$$\sigma_{ia} = C_{4iL} - C_{4ip} \tag{27}$$

where:

C_{4iL} - concentration of the i-th substance at the left river bank below the power plant

C_{ip} - concentration of the i-th substance at the right river bank above the power plant

The determination of relations between the increase of concentration at longitudinal section and the discharge of heated waters –

The outline of calculations was presented in the part devoted to the algorithm of the FUNCT-3 program. The value ΔC_i used in approximating the function was calculated from:

$$\Delta C_i = \bar{C}_{3i} - \bar{C}_{4iL} \tag{28}$$

where:

$\bar{C}_{3i}$ = average concentration value of the i-th substance upstream from the power plant

$\bar{C}_{4iL}$ = average concentration value of the i-th substance downstream from the power plant

The values of regression coefficients calculated by means of the APROX-3 program are given in table 31.

Table 31. Regression coefficients for model 2

Regression coefficient	D.O	BOD_5	Ammonia	Nitrite	Nitrate	Organic nitrogen
b_0	-3,601	0,462	0,503	0,062	0,014	0,326
b_1	0,117	0,029	-0,003	-0,001	0,0207	0,0162
b_2	[illegible]	-0,052	-0,003	-0,0008	-0,0019	-0,0007
b_3	0,00001	0,0001	-0,0001	0,0002	-0,0004	0,0006
b_4	-0,216	0,122	0,017	0,0093	-0,0095	-0,1553

Conclusion

The analysis of relations between the changes in concentration of given parameters of water quality and factors characterising the influence of heated waters has shown that these relations are weak. In tabl. 32 we can see variance coefficients for different parameters of water quality and types of mathematical models, (V_i).

$$V_i = \frac{\sqrt{\sum^{NPOM} (\Delta C_i - y_i)^2}}{\sqrt{NPOM} \cdot \overline{\Delta C}_i} \qquad (29)$$

The calculated coefficients are characterised, first of all, by the degree of reality in representing the relations by a proposed mathematical model. In the case when variance coefficient equals zero we can assume that the proposed model represents the

Table 32. Coefficients of variance

Coefficients of variance	For C_1			For C_2		
	for three variables functions	for four variables function fourth variable		for three variables functions	for four variables function fourth variable	
		load	concentrat.		load	concentrat.
Oxygen	1.986	1.724	2.760	1.400	1.397	1.929
BOD_5	6.982	5.236	5.462	3.791	2.548	2.971
Ammonia	90.000	80.002	80.007	5.000	5.385	6.042
Nitrites	3.000	2.558	2,375	-	-	-
Nitrates	8.043	8.740	8.266	6.536	7.541	5.967
Organic Nitrogen	9.091	22.434	22.964	-	13.460	15.740

reality ideally. In our case the comparison of variance coefficients for a given parameter of water quality has helped in determining which model is the best.

On the basis of calculated variance coefficients it can be stated that for BOD_5 parameters, for dissolved oxygen and nitrites the correlation between the obtained results is average. For water quality parameters such as nitrates, organic nitrogen and ammonia it was observed that correlations in the described models are weak. It is also worth marking that in the case of four variable function in which the fourth is the load of the substance, upstream from the power plant the variance coefficient decreases.

Thus it seems that the proposed mathematical model 2 characterises better the occurring phenomena than model 1. The final form of the model 2 can be written as follows:

$$y_i = b_{0i} + b_{1i} \cdot q/Q + b_{2i} \cdot \Delta T_{4i} + b_{3i} \cdot T_3 + b_{4i} \cdot \bar{C}_{3i} \cdot Q \qquad (30)$$

under the condition that it is applied only for such parameters as the changes in BOD_5 and the changes in concentration of dissolved oxygen and nitrites.
The analysis of regression coefficients shown in tabl.31 shows that the model given in the formula 30 has the character of mean deviation function i.e. even with large changes in the three variables q/Q, ΔT_4 and T_3 the changes of y_i are small. Only in the case of changes of the fourth variable $\bar{C}_{3i} \cdot Q$ the value of y_i is very sensitive. The comparison of regression coefficients for the model referring to oxygen shows that the changes in the amount of oxygen depend on the value of q/Q, on the temperature ΔT_4 and, in a smaller degree, on the temperature upstream from the power plant T_3. In the case of BOD_5 the above comments are identical, with this difference that the changes in BOD_5 depend also on the load of organic compounds upstream from the power plant. The analysis of regression coefficients for the model describing the changes in nitrite concentrations shows that the increase in concentration depends, first of all, on the increase of temperature.

It can be assumed then, that the given model satisfactorily presents the physical and chemical conditions caused by the thermal water discharge, which influences the water quality.

THE EFFECT OF TEMPERATURE ON THE SIZE DISTRIBUTION OF SUSPENDED PARTICLES IN WATER

Introduction

Downstream from the heated water discharge point from the Kozienice power plant the Vistula river is used as a source of water supply. One of its more important users is the Warsaw municipal water works. Because of the use of filtration methods agglomeration of particles suspended in the intaken water is essential. Hence the problem how the heated water from the Kozienice power plant can affect agglomeration of particles suspended in the Vistula water.

Investigation of this problem was carried out in two ways: in the natural river habitat and in the laboratory. In the first case observations were made in the area of the heated water discharge station 3, 4, 4a, IV ; in the other-samples of the Vistula water which were being kept for a given period of time at a given temperature were analyzed.

Research on the size distribution of suspended particles was carried out by means of the Coulter Counter.

Up to now the Coulter Counter has been widely used in such fields of science as biology and geology 32, 33, 34 , whereas in water investigation it has been mainly applied in oceanography. The published works making use of the Coulter Counter dealt with such problems as determining the size distribution of suspended particles in surface water, depending on the distance from the shore and the depth of water reservoirs, and on the water current distribution 35, 36, 37, 38 .

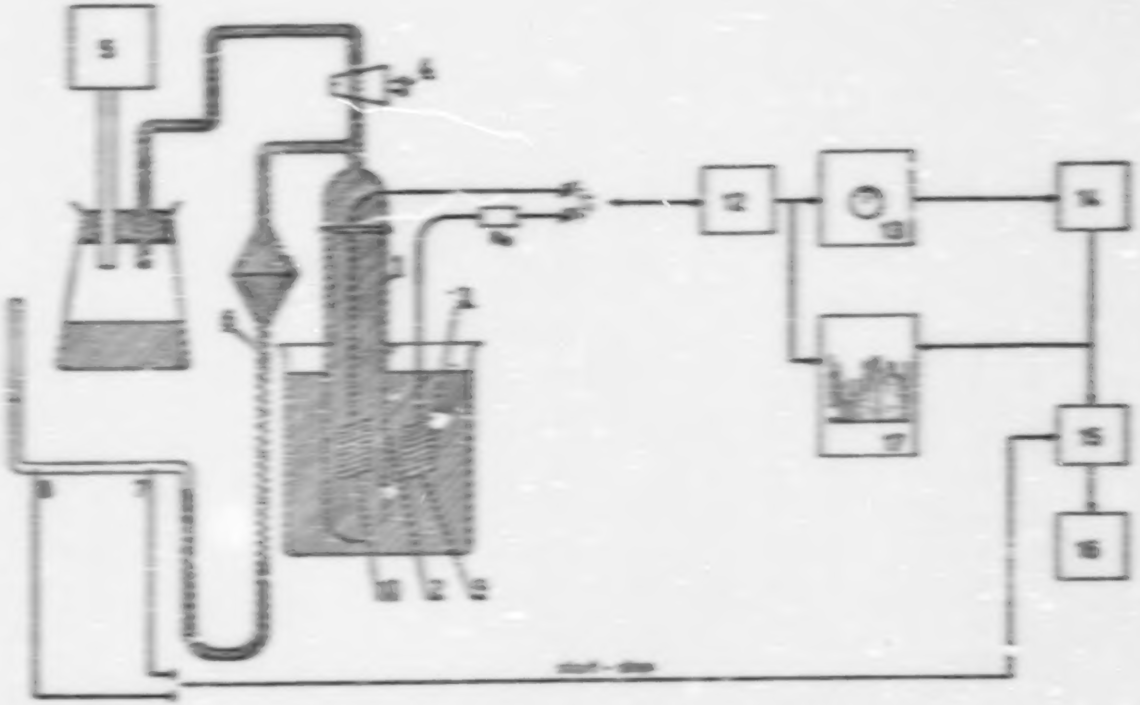
In the accessible bibliography no publication on the effect of water temperature on the size distribution of suspended particles has been found.

Materials and methods

The principle of the measurement of suspended particles by means of the Coulter Counter -

The Coulter Counter, Model B, Coulter Electronics Inc., Hialeah, Florida, USA, was used in this research.

The Coulter Counter is an electronic device measuring the size and the number of particles suspended in an electrolyte by means of the conductance method. Its diagram is shown on Fig.25.


5
4
12
13
14
6
1
11
17
15
8
7
10
2
9
16
start-stop

1—Aperture tube
2—Aperture
3—Electrolyte beaker
4—Vacuum regulator
5—Vacuum pump
6—Mercury manometer

7—Start
8—Stop
9,10—Electrodes
11—DC source
12—Pre amplifier

13—Threshold circuit discriminator
14—Pulse amplifier
15—Counter timer
16—Digital register
17—Scope

Fig.25. Schematic diagram of Coulter Counter

Two electrodes 9 and 10 placed in electrolyte 3 are separated from each other by an aperture tube 1, with an aperture 2 in its lower part. There is a current of constant voltage between the electrodes. By means of a pump the electrolyte is made to flow through the aperture. When a suspended particle appears in the aperture, resistance between the electrodes changes, which results in an impulse - a short-lasting change in the voltage of the system. The amplitude of an impulse is proportionate to the size of a particle. After passing the main amplifier 12 the impulse passes to threshold circuit (discriminator) 13, which sends only the impulses of a given amplitude to the counter. On repeating the analysis of the same sample at different levels of discrimination we obtain a curve of distribution of given suspended particles.

The vacuum system is supplied with a mercury manometer, which allows for a constant flow of a given volume of the analysed sample (50, 500 or 2000 microliters) through the aperture.

Calibration of the instrument is done by means of mono-sized particles placed in electrolyte. Plastic spheres or pollen of appropriate plants are used here. The electrolyte should now be the same as the one used for testing a sample. The particles whose diameter equals to 5 - 20 percent of the aperture diameter are best for calibration. The calibration constant k is computed from the formula:

$$k = \frac{V}{I \cdot A \cdot t_L}$$

where:

V = volume of calibrating material, μm^3

I = aperture current setting

A = amplifier setting

t_L = lower threshold setting

This calibration constant is valid as long as no changes are made except in I, A, and t_L. Any given combination of dial settings will represent a specific particle volume and may be determined by the formula:

$$V = k \cdot I \cdot A \cdot t_L$$

The particle diameter d equivalent to a sphere volume is calculated from the formula:

$$d = 1,241\sqrt[3]{V}$$

Accurate results of particle measurement by the Coulter Counter can be only obtained when particles pass through the aperture one by one. However, it was proved that multiple passages are inevitable. The most frequent of coincident passages are double ones. And that is why they were taken into account in the final adjustment of measurement results.

Such coincident passages of the suspended particles analyzed with the Coulter Counter make the result of the counting too low. They also cause some displacement of the size distribution curve; this means that the impulses which have been counted are below a given threshold setting.

Because of the coincident passages some correction is necessary to introduce to the obtained results. Coincidence correction factor is calculated as follows:

$$p = 2,5\left(\frac{D}{100}\right)^3 \cdot \left(\frac{500}{v}\right)$$

where:

D = aperture diameter in μm
v = counted sample volume in μm^3

Hence the coincidence correction n'' is counted and added to the average results taken from the counter n':

$$n'' = p\left(\frac{n'}{1000}\right)^2$$

In practice, in order to retain an overall accuracy of results (about 1 %), the coincidence corrections should be about 10 %. Therefore, an optimal number of particles in a sample of a given volume and for a given aperture diameter has been determined by testing.

Procedure

The samples of water from Vistula were fixed by a 4 % solution of sublimate added in quantities of 2 cm^3/l and stored for 24 hours at room temperature.

All solutions of reagents added to a tested sample were first filtered through a membrane filter (procedure repeated twice).

Before the commencement of the analysis the thoroughly mixed samples were filtered through a plankton net no.25 net mesh diameter ca.55 μm) applying a vacuum water pump. Thus that suspension whose size exceeded the required size for used aperture (100 μm) was removed.

After filtering the samples for laboratory investigation they were put in beakers and placed in thermostats regulated for temperatures of 5, 10, 20, 32°C. Two tests were conducted: one for samples kept in thermostat for 15 min. and the other kept there for 5 hours.

Immediately before counting the particles such an amount of a 25 % solution of sodium chloride was added as to give a concentration of electrolyte in the sample of 1 %.

The measurements of suspension by means of the Coulter Counter was made according to the instructions provided by its producers (19). The apparatus was calibrated with polystyrene particles of 18.04 μm diameter with the following parameters:

$t_L = 26$

$I = 1$

$A = 2$

The calibration constant thus calculated equalled k = 58.7

The sample volume, programmed with a mercury manometer equalled to 500 μl. This, at aperture diameter of 100 μm gave a coincidence constant "p" of 2.5.

The precision of the applied method is given in enclosure 7.

Results

The results of measurements are given in Enclosures 101 - 109 and they contain the following data:

- number of suspended particles in 500 μl of a sample

$\bar{n}'$ = average from 3 reading

n = $\bar{n}'$ after including the coincidence correction (v.Materials and Methods).

- extremal size of given distributions of counted particles:

V = particle volume in μm^3 (v.Materials and Methods)

d = particle diameter calculated from particle volume in μm.

- weigh percentage of particles, grouped above a given boundary of size calculated on the basis of results n, $\bar{V}$

$$Wt = \Sigma(\Delta n)\,\bar{V}$$

where:

Δn = difference in the amount of particles in consecutive pairs of results.

$\bar{V}$ = average particles size in a given distribution

Example of calculation:

n	V	Δn	$\bar{V}$	$(\Delta n)\bar{V}$	$\Sigma(\Delta n)\bar{V}$	Wt %
0	188000					
		1	141000	141×10^3	141	3.4
1	94000					
		4	70500	282 "	423	10.3
5	47000					
		16	35250	564 "	987	24.1
21	23500					
		176	17625	3102 "	4089	100
197	11750					

A set of all enclosures included in a separate part of the work entitled the Suplement to "Studies on the Effects of Heated Waters Discharged from the Kozienice Power Plant on the physico-chemical processes in the Vistula River and on the Water Quality" Research Grand No. PR-05-532-5. Basic Data. Warsaw, Poland 1976.

Discussion

Influence of the heated water discharge on the suspended particles in the Vistula river -

The research on the influence of heated water discharge from the Kozienice power plant on the size distribution of suspended particles in Vistula was conducted at temperatures differences of water upstream and downstream from the power plant, equalling from 1.6 to 6.0 °C (tabl. 33). The difference between the right and left river bank below the power plant also reached 6 °C. On the other hand, the heating of water in the power plant reached 10.1 °C in relation to intake water from the river.

The spectrum of suspended particles obtained on the basis of the results embraced particles of volume greater than $18\ \mu m^3$ or of a $3.3\ \mu m$ diameter.

The total amount of particles in suspension, depending on a sample, was between 11 and 83 thousand in $0.5\ cm^3$ of water. Particles of volume exceeding $18784\ \mu m^3$ ($33\ \mu m$ diameter) either did not occur at all, or occurred much less often than particles of smaller size.

The differences between the total amounts of particles in samples from stations influenced by heated water (4 l, 4al, IV) and from stations not influenced by heated water (3 l; 4 r) had either a positive or negative sign (tabl. 34, 35, 36). Absolute values of these differences do not depend on temperature.

It can be noticed, though, that there is a certain regularity of changes of total amount of suspended particles in relation to seasons. From October on there is a clear decrease of the amount of particles at all stations. This decrease exceeded 90 % of all particles observed in summer months. This points to a considerable influence of water organisms on the amount of suspension in the Vistula, which was proved recently by biological research.

The difference between parallel results for stations influenced by heated water and not influenced by it (4 l - 3 l; 4al - 3 l; 4 l - 4 m; 4 l - 4 r; IV - 3 l), on the basis of the Student test at changeability level of 5 % should be considered as unessential.

A comparison of the number of particles in the Vistula water in periods of highest temperature differences between heated and unheated water was done (between stations No 4 l - 3 l; 4 l - 4 r) i.e. in 9.1, 10.21, 11.11 and 12.2 1975. The increase of temperature exceeded 4 °C.

Table 33. Temperature of Vistula water during the sampling

Date	Temperature °C					Difference temp. °C		
	Stations					Stations		
	3 l	4 l	4 r	4al	IV	4 l - 3 l	IV - 3 l	4 l - 4r
7.23.75	21.0	22.6	-	21.8	-	1.6	-	-
8.27.75	20.4	22.6	-	22.2	-	2.2	-	-
9.1. 75	18.0	22.6	-	21.2	-	4.6	-	
9.10.75	16.4	19.4	-	18.8	-	3.0	-	-
9.16.75	16.4	18.8	17.0	18.7	24.2	2.4	7.8	1.8
10.7. 75	12.8	14.0	13.0	13.4	21.4	1.2	8.6	1.0
10.21.75	9.6	13.8	9.3	12.2	20.5	4.2	10.9	4.5
11.11.75	5.0	9.4	5.2	7.2	17.2	4.4	12.2	4.2
12.3. 75	1.4	7.4	1.4	4.2	19.5	6.0	18.1	6.0

Table 34. Changes of total number of suspended solid (3.2 - 10 μm) along the Vistula river

Date	Stations			Difference	
	3 1	4 1	4el	4 1 - 3 1	4el - 3 1
7.23.75	33879	40349	40312	+ 6470	+ 6433
8.21.75	83239	11057	23032	-72182	-60207
9.1. 75	45717	57050	60757	+11333	+15040
9.10.75	52625	41861	36775	-10764	-15850
9.16.75	36242	36981	42571	+ 739	+ 6329
10.7.75	14388	16240	15941	+ 1852	+ 1553
10.21.75	10748	17201	16754	+ 6453	+ 6006
11.11.75	12311	11273	14243	- 1038	+ 1932
12.3. 75	15294	21140	14463	+ 5846	- 831

Table 35. Changes of total number of suspended solid (5.2 - 33 μm) across the Vistula river

Date	Stations			Difference	
	4 l	4 m	4 r	4 l - 4 m	4 l - 4r
9. 16.75	36981	33094	34205	+ 3887	+ 2776
10.7. 75	16240	8582	11631	+ 7658	+ 4609
10.21.75	17201	12578	17875	+ 4623	- 674
11.11.75	11273	13995	13282	- 2722	- 2009
3.12.75	21140	17577	14235	+ 3563	+ 6905

Table 36. Changes of total number of suspended solid 5.2 - 33 μm in Vistula water after passing through cooling system

Date	Stations		Difference
	3 l	4 l	4 l - 3 l
9. 16. 75	36242	30165	- 6077
10. 7. 75	14388	22996	+ 8608
10. 21. 75	10748	15730	+ 4982
11. 11. 75	12311	22102	+ 9791
12. 3. 75	15294	13958	- 1336

The curves of percentage of particles of a given size in samples from stations 3 l, 4 l, and 4al had similar shape. Only in two cases were the curves closely adjacent to each other (Fig. 26, 27). In the two remaining cases we could observe a certain dislocation of the curves in relation to each other (Fig.28,29). Clear differences in relation to the curve for station upstream from the power plant were marked in curves for water in the discharge channel and for water at station 4a. Taking into consideration that the curve for water in the discharge channel was placed interchangeably higher or lower in relation to the curve for station 3, it should be supposed that the temperature was not the only decisive factor shaping the spectrum of suspension.

In the case of curves for stations 3 and 4 (Fig.28, 29) we can notice a larger or smaller displacement of the curve scale for stations being under a direct influence of heated water. This dislocation is especially clearly seen on Fig. 28 and points to a decrease of dispersion of suspension in heated water. Thus, at station 4 l suspended particles of diameter exceeding 10 μm constituted 47 %, and particles of a diameter exceeding 20 μm 12 %, while at station 3 l the amount of particles of analogous sizes was 39 % and 8 %.

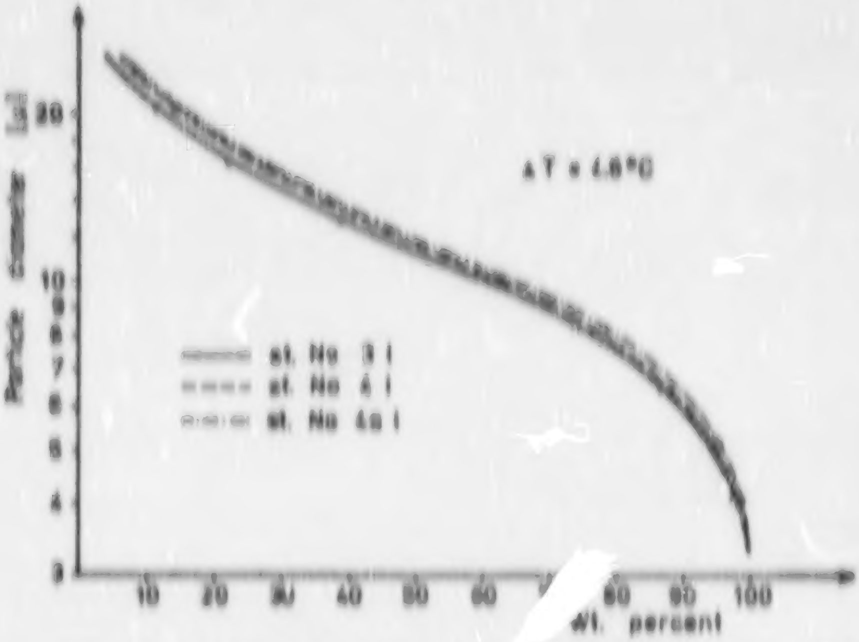


Fig.26. Size distribution of particles suspended in Vistula water 9.1.1975

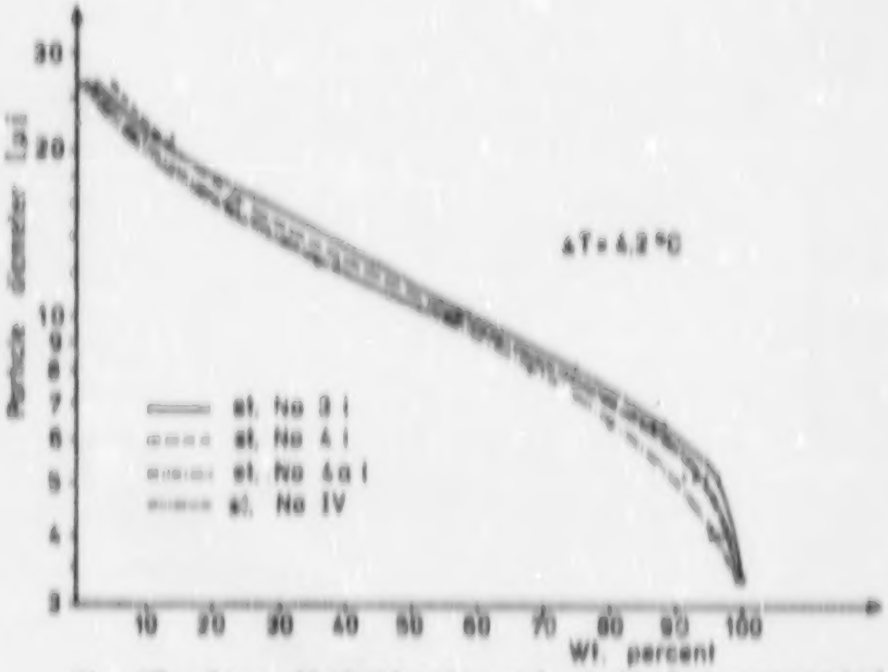


Fig.27. Size distribution of particles suspended in Vistula water 10.22.1975

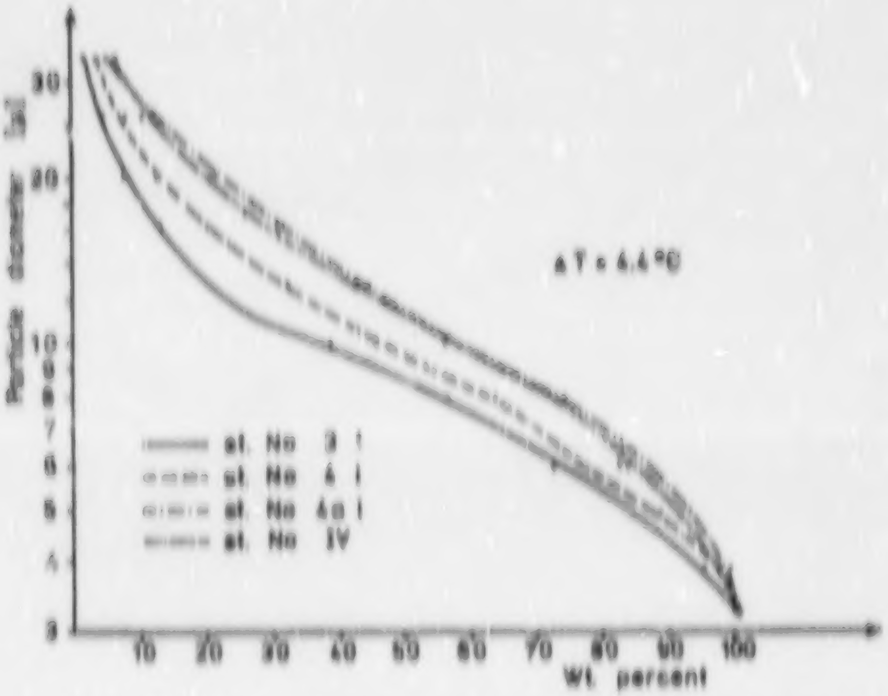


Fig.28. Size distribution of particles suspended in Vistula water 11.11.1979

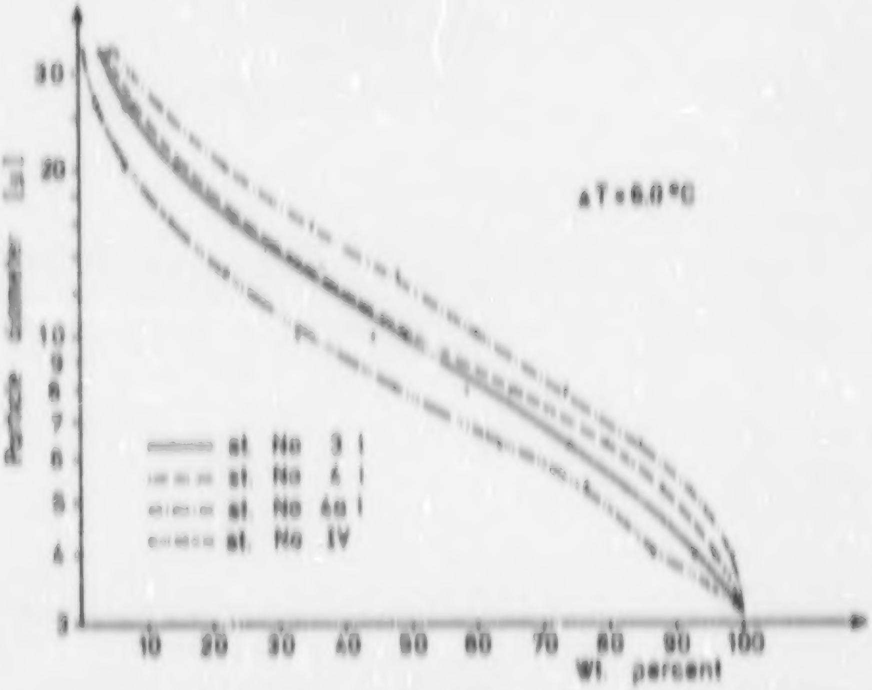


Fig.29. Size distribution of particles suspended in Vistula water 12.2.1979

Influence of temperature on the suspension in water -

The results of laboratory tests gave a spectrum of suspension in water covering also particles larger than 10784 μm^3. The general number of particles in suspension could be estimated as several thousand in 0.5 ml of water.

Fifteen minute test - The fifteen minute test was conducted twice with two different samples of surface water. Three samples of the same type of water were incubated. The measurement of suspension was done separately for each sample (enclosures 116 - 117). Averages from the total number of counted particles are given in tabl. 37.

Table 37. Fifteen minutes test: average of total number of particles

Sample No	5 °C	10 °C	20 °C	32 °C
1	29826	49032	50190	50848
2	68439	53192	49965	62861

Starting with the number of particles in the temperature of 20°C in both cases, a certain increase in the amount of particles was noticed when temperature was increased. A decrease of temperature caused a decrease in the amount of particles in one case, and an increase in that amount the other.

The analysis of the size distribution of incubated particles (15 min. test) has not shown any decided influence of water temperature on suspension.

Five-hour test - The five-hour test was conducted six times with six different samples of water. Two samples were tested in three parallel repetitions (samples 5 and 6). The measurement of suspension was done separately for each sample (enclosures 118 - 130). Total number of particles are given in tabl.38.

Table 38. Five hours test: total number of particles

Sample No	5 °C	10 °C	20 °C	32 °C
1	80414	43363	55371	-
2	79659	37419	36140	39024
3	39602	44692	20877	43532
4	47165	33036	49521	33947
5 x	36109	39241	46209	43218
6 x	42523	39108	40561	27379

x averages from 3 measurements

Starting with the number of particles in 20 °C it can be noticed that in most cases the total number of particles increased when the temperature decreased down to 5 °C; only in one case did the amount of particles decrease, which, however, did not exceed the boundary of error of measurement. When temperature increased, the total amount of particles showed a tendency to decrease.

The influence of temperature on the size distribution of particles in water is illustrated by curves of weight percentage of particles above a certain size (fig.30, 31). On these curves it shown that an increase in temperature caused a decrease of number of particles larger size. Particles of a diameter above 10 µm constituted percent :

temp. 5 °C : 72 - 80
temp.10 °C : 65 - 75
temp.20 °C : 50 - 69
temp.32 °C : 30 - 35

The results of research conducted on the influence of temperature on the amount and size distribution of suspension par-

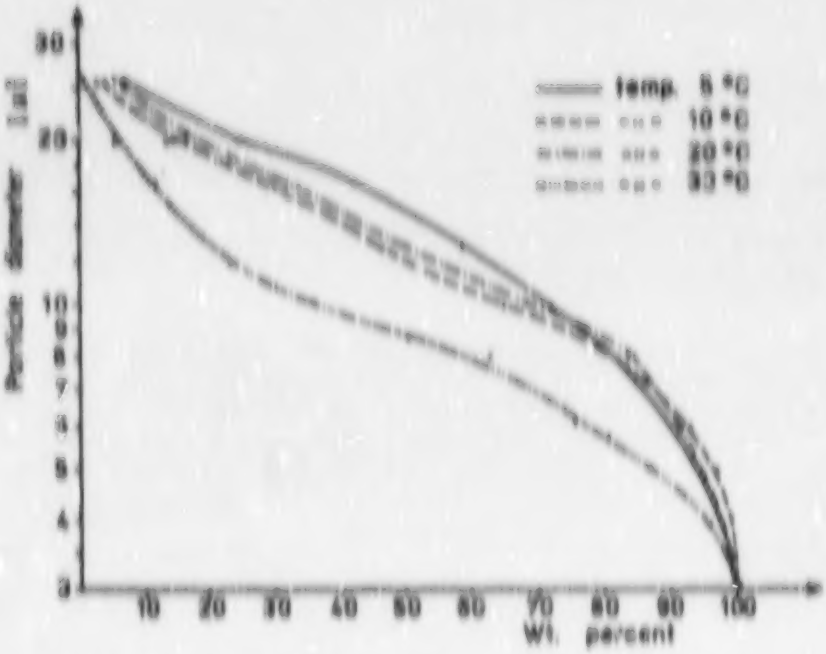


Fig.30.The influence of temperature on the distribution of particles suspended in the water

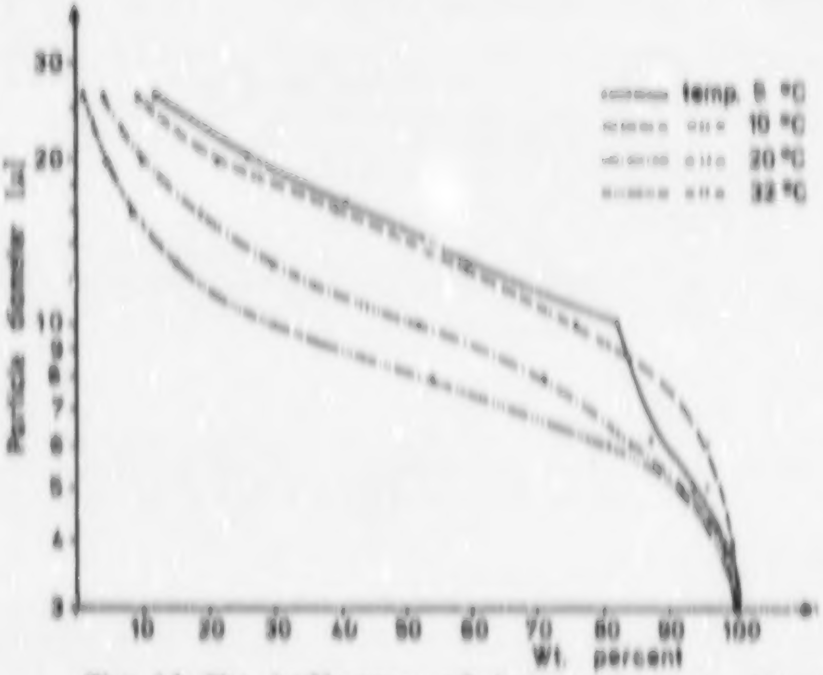


Fig.31.The influence of temperature on the distribution of particles suspended in the water

ticles by means of the Coulter counter have shown what follows:

In the period of research the total amount of particles of a 3.3 - 33.0 μm diametrin Vistula river equalled from 11 to 80 thousand in 0.5 cm^3 of water.

The heating of Vistula water by the Kozienice power plant did not influence unequivocally the total amount of particles in a given sample of water. The differences in the amount of particles in water downstream and upstream from the power plant equalled from -72.000 to +11.000. Most often the increase of suspension amount was noticed in the heated area of the river.

A high decrease more than 40 % of the amount of particles in autumn and winter was noticed in relation to summer, and it was caused by a considerable influence of water organisms.

The analysis of percentage of particles above a given size in samples of heated and unheated water did not point to unequivocal differences. In some cases we could notice a tendency of increasing the number of larger particles in heated water.

The results of laboratory tests have also not shown a definite dependence of the size distribution of particles on temperature. In some cases one could observe a decrease in the amount of larger particles in higher temperatures.

Conducted tests have confirmed the usefulness of the Coulter Counter in the research on the water suspension. At the same time it should be stated that the methodology of this type of tests requires certain improvement especially in the field of preservation and storage the water samples.

THE INFLUENCE OF TEMPERATURE ON THE BIOCHEMICAL PROCESSES OCCURRING IN THE VISTULA RIVER

The aim of the investigation was learn the biochemical changes and the changes in the water quality resulting from them in extreme temperatures, which could not be observed in field investigations on the influence of the heated water from the Kozienice power plant on the quality of water in Vistula.

Materials and methodology

The laboratory investigations on the biochemical processes in relation to temperature were conducted in the wide range of temperatures from 4 to 40 °C.

A sample of Vistula water, after homogenising and preparing in appropriate temperature, was placed in a series of bottles of ca. 300 cm³ capacity and tightly stoppered, without leaving a single bubble of air under the stopper. In the case when in tested temperature the oxygen saturation was greater than 100 %, the excess of oxygen was removed. The bottles were then placed in thermostats in which temperatures were kept a few degrees apart, within the range from 4 to 40°C, during five 24-hour periods or longer. In these samples at the beginning and then every day the following parameters were checked and marked: dissolved oxygen, ammonia, nitrites, nitrates, organic nitrogen and pH. Consecutive measurements were done by methods described on page 60.

Research results

Oxygen processes –

Several series of tests on the changes in the oxygen amount in Vistula as caused by occurring biochemical processes of decomposition of various organic compounds at different temperatures were conducted. The results show that a decrease of oxygen concentration in water due to the processes of biochemical decomposition of organic substances was very clearly dependent on temperature. Several measurements were done which, in spite of a fairly large irregularity can enable us to see the character of the process. It is illustrated on figure 32, showing oxygen consumption and on figure 33 showing changes of BOD_5 of the Vistula river. At 4 °C biochemical processes practically stopped; at 10 °C oxygen consumption was also small and during the next five days it did not decrease below 4 mg/l O_2. At 20 °C this limit was exceeded in three days. At 30 °C in four days the water was practically deoxidised. Within the range of temperatures up to 30 ° an increase of temperature was accompanied by increase of oxygen consumption. In 40 °C oxygen consumption decreased again. It can be explained by a slow-down of microbial activity which is responsible for biochemical decomposition of organic substances and a decrease of oxygen intake.

The results show that the rate of oxygen consumption in water which depends on biochemical processes is variable and dependent on the quantity and quality of polluting substances and also on water micro-organisms; it varies among different samples of water taken from different places of the river and at different times.

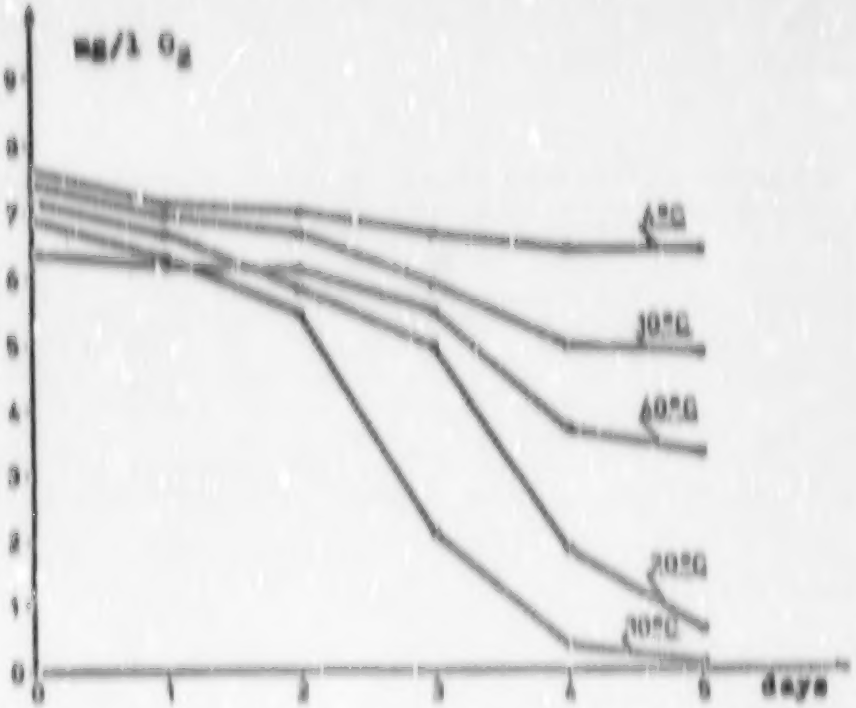


Fig. 32. Decrease of D.O. concentration in water in various temperatures, June 1974

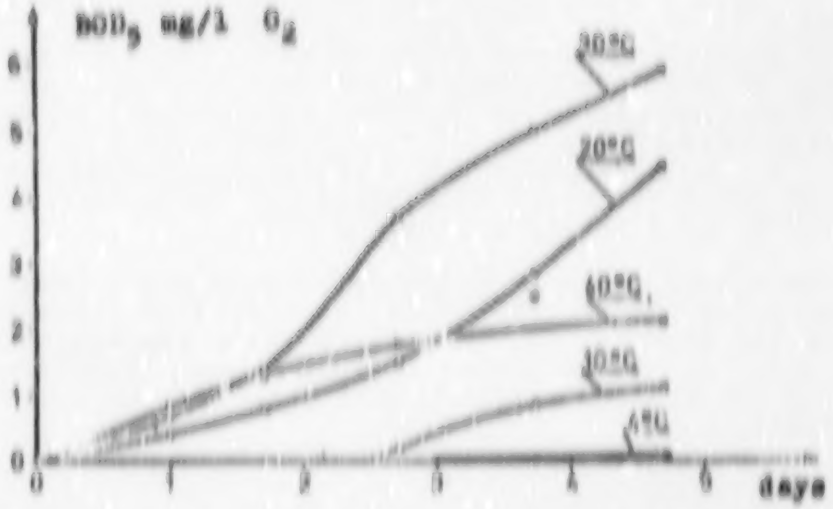


Fig. 33. Changes of BOD_5 of Vistula water in various temperatures mean values from 5 measurements, 1974

Nitrification -

Several measurements of nitrification processes in Vistula were done.During investigations of the effect of temperature on changes of ammonia concentration two cases were observed: the first for ammonia concentration within the range of several mg/l and the second for concentrations within the range of hundredths of mg/l. In the first case (fig.34) a considerable decrease of ammonia concentration occurred. Dependence on temperature was clearly marked. The lowest decrease occurred at the temperature of 4 °C, and the highest at the temperature of 20 °C when the ammonia concentration decreased down from 2,6 to 0,3 mg/l N. At the temperature of 30 °C the speed of ammonia oxidation was subject to a repeated decrease, and at 40 °C the process was again as slight as at 4 °C.
The obtained results prove that the nitrification process is clearly dependent on temperature.

The initial concentration of nitrites in the tested water was always small, below 0.1 mg/l N. The changes in the nitrite concentration were largely dependent on temperature (fig.39, tabl.39). At low temperatures of 4 and 10 °C the amount of nitrites remained at an almost unchanged level. A considerable increase in the concentration of nitrites was observed in temperatures of 20 and 30 °C. However, at the temperature of 40 °C we could see that the nitrification process stopped and concentration of nitrites remained at the same level throughout the period of incubation. The curves illustrating the increase of nitrites in the temperatures of the temperatures of 20° and 30° point to an acceleration of the process of involving of nitrites during incubation. In some cases a decrease of the amount of nitrites after four days of incubation was observed, which points to an oxidation of nitrites into nitrates.

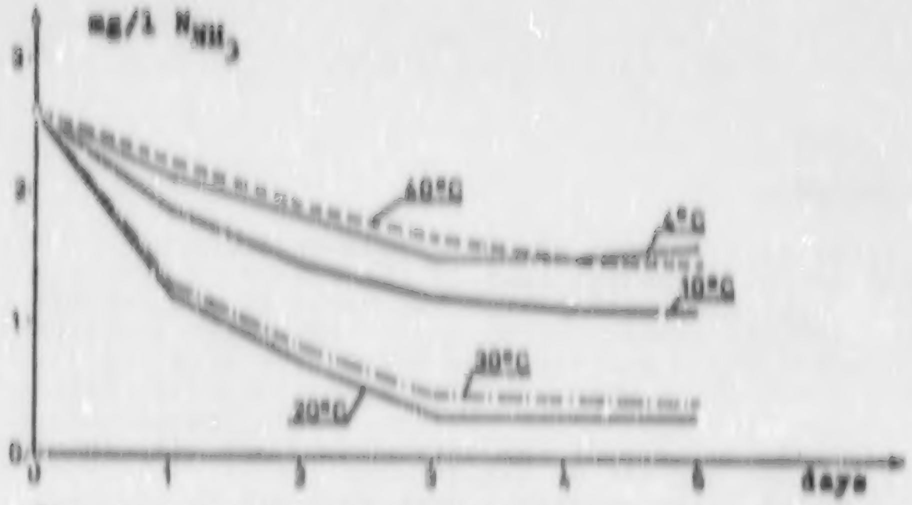


Fig. 34. Decrease of ammonia concentration in water in various temperatures, April 1974

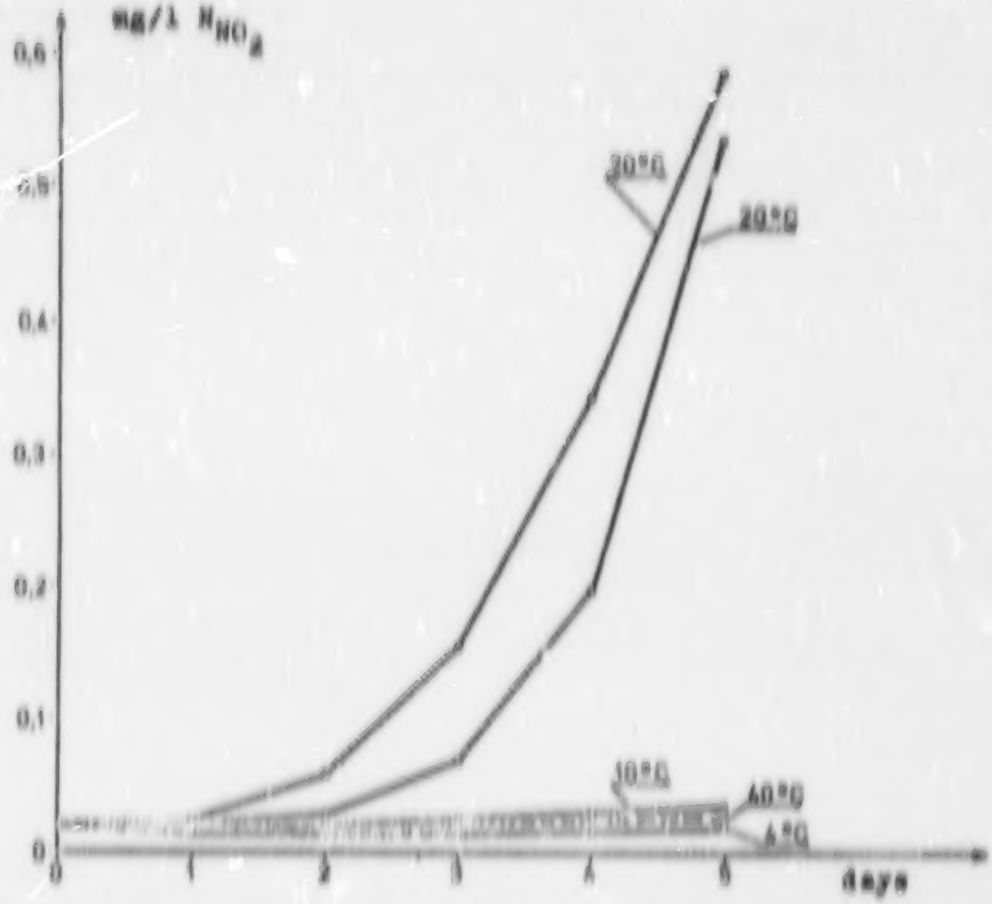


Fig. 35. Changes of nitrite concentration in water in various temperatures, March 1974

Table 39. Changes of nitrite concentration in Vistula water. March 1974. The initial concentration of ammonia = 3,8 mg/l N

Temp. °C	Nitrite concentration, mg/l N					
	0	0,7	1,7	2,7	3,7	4,7
1	0,032	0,039	0,047	0,034	0,040	0,033
10	0,032	0,037	0,041	0,043	0,034	0,058
20	0,032	0,048	0,059	0,110	0,108	0,950
32,5	0,032	0,055	0,160	0,312	0,43 x)	1,14 xx)
40	0,032	0,038	0,048	0,031	0,039	0,070

x) increase of nitrate 0,05 mg/l N

xx) increase of nitrate 0,07 mg/l N

Discussion

Determination of k_1 constant changes in various temperatures -

The samples of water with low ammonia concentration were chosen for calculations. In such cases BOD$_5$ was caused only by the process of oxidation of organic carbon compounds. The possibility of calculation of k_1 constant with the help of various methods has been checked. The classic method of Reed Thierault (40) was chosen as the best one in this case.
The results for the waters of the Vistula were as follows:

Date	Temp. °C	k_1 d^{-1}	Θ_1
January 1973	10 20 30	0,097 0,156 0,216	1,041
March 1973	4 10 20 30	0,109 0,126 0,160 0,202	1,024
June 1974	10 20 30 40	0,065 0,083 0,108 0,136	1,025

The averaged and rounded $k_{1(20°C)} = 0,1\ d^{-1}$.

Determination of the rate of nitrification in different temperatures -

The water from the Vistula river near Kozienice was investigated; it was heavily polluted with ammonia in winter. In laboratory investigations, during incubation, the most significant changes at various temperatures were observed in the case of nitrites involving. The following relationship was used for defining the rate of nitrification:

$$\log \frac{y_1}{A - y_1} = \alpha_1 t - a_1 \qquad (1)$$

where:

y_1 - the concentration of nitrites in water after incubation in mg/l N

A - initial ammonia concentration in mg/l N

t - time

α_1 - ammonia oxidation rate factor

a_1 - constant of the process of nitrification

The above presented data served as the basis for the graphs on which the time t is shown on x-axis and y-axis contains the expression $\log \frac{y_1}{A - y_1}$ (fig.36). The marked points formed nearly straight lines, the slope of which indicates the value of α_1. The results are presented in tabl. 40. A distinct dependence of α_1 factor on temperature has been observed. For easier evaluation of temperature influence on α_1 values, the ratios of α_1 values at different temperatures to this value at 32.5°C were calculated. This particulate temperature of reference was chosen, because of its presence in all series.
Average results are presented below:

temperature	°C	10	20	25	27.5	30	32.5	35	40
$\frac{\alpha_1}{\alpha_{32,5^0C}}$	6	51	143	131	123	111	100	85	48

These values marked on the graph (fig.37) have shown that the maximum α appears near 20 °C and at higher temperatures α decreases.

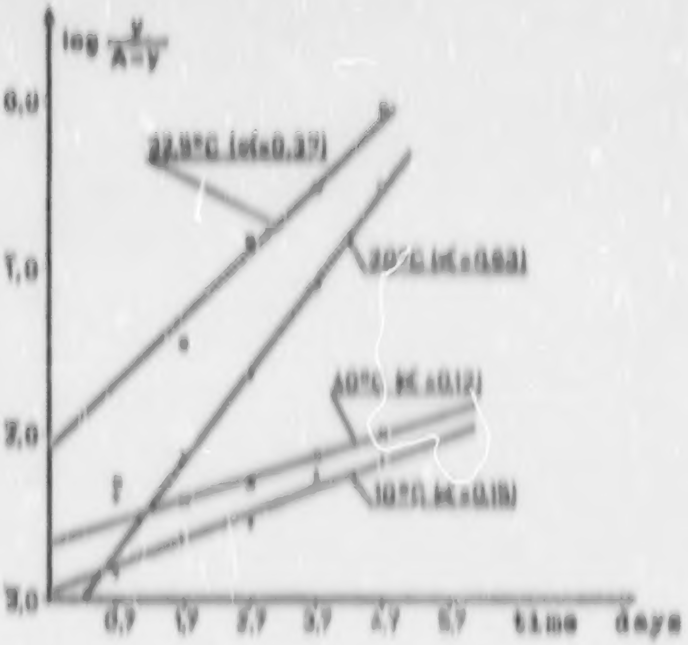


Fig. 36. The course of nitrification process of Vistula water in various temperatures, March, 1974. The initial concentration of ammonia A = 3.8 mg/l N

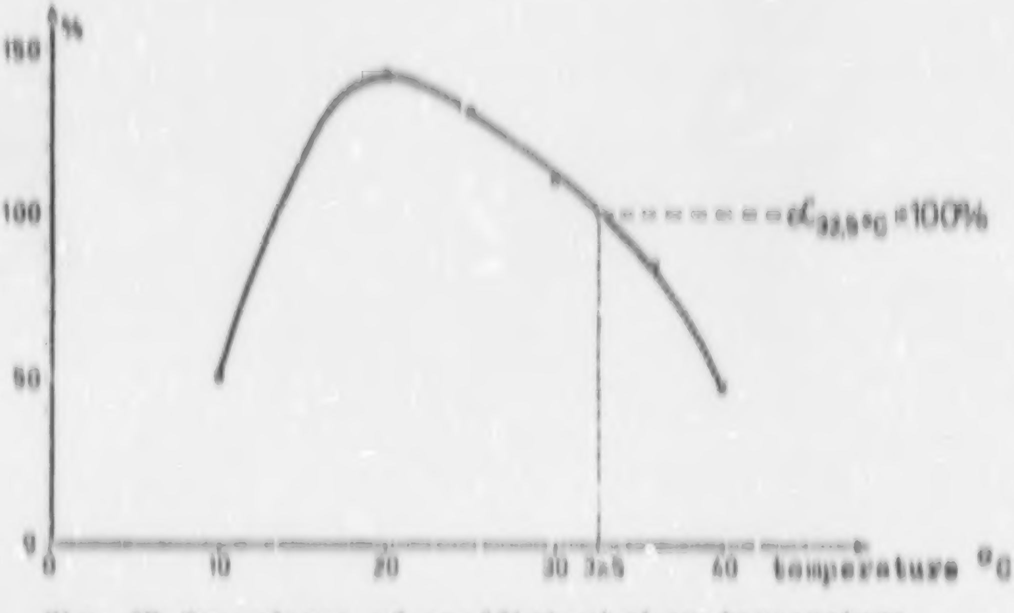


Fig. 37. Dependence of coefficient α on temperature (α for various temperatures calculated in percent of $\alpha_{32,5°C}$ =100%)

Table 40. Results of nitrification process study

Period	Station	Temp. °C	α, d^{-1}	t, d	A mg/l N_{NH_4}
		10	0,19		
3.74	below Pulawy	20	0,35	5,7	2,5
		32,5	0,34	5,6	
		10	0,23		
3.74	below Kozienice	20	0,54	4,9	2,7
		32,5	0,40	4,7	
		40	0,26		
		10	0,19		
3.74	below Kozienice	20	0,63	5,6	3,8
		32,5	0,37	5,0	
		40	0,12		
6.74	below Kozienice	10	0,24	9,2	2,5
		20	0,53	3,4	
		32,5	0,47	2,5	
		25	0,54	6,5	
2.75	upstream Pulawy	27,5	0,66	6,2	1,7
		32,5	0,60	6,2	
		37	-		
		30	0,66	4,4	
2.75	Czerniaków	31,5	0,59	4,6	
		35	0,48	5,2	
		25	0,68	5,5	
3.75	below Kozienice	27,5	0,49	5,1	1,4
		30	0,58	5,0	
		32,5	0,52	5,7	
		35	0,46	5,5	

Consumption of oxygen takes place during nitrification. The course of this process can be shown as follows:

$$NOD = 3.22\ y_1 + 1.11\ y_2 \qquad (2)$$

where:

NOD = nitrogen oxygen demand

y_1 = concentration of nitrites after incubation in mg/lN

y_2 = concentration of nitrates after incubation in mg/lN

Because the nitrification at the second stage (oxidation of nitrites into nitrates) was very slow and in most cases was not observed at all, the formula can be shortened into the following form:

$$NOD = 3.22\ y_1$$

The line showing the consumption of oxygen according to the above presented equation has taken the form of the letter S (fig. 38). That graph has a long section resembling a straight line of the following slope:

$$\frac{3.22 \cdot 2.303 \cdot A \cdot \alpha}{4}$$

which can be obtained from the transformation of equation:

$$y = \frac{A \cdot 10^{\alpha t - a}}{1 + 10^{\alpha t - a}}$$

$$\frac{dx}{dt} = 2.303\alpha A \frac{10^{\alpha t - a}}{(1 + 10^{\alpha t - a})^2}$$

When $t = t_1$, which equals half of the time of reaction, then

$$\left.\frac{dx}{dt}\right|_{t=t_1} = \frac{2.303 \cdot \alpha \cdot A}{4}$$

taking into consideration the equation (2)

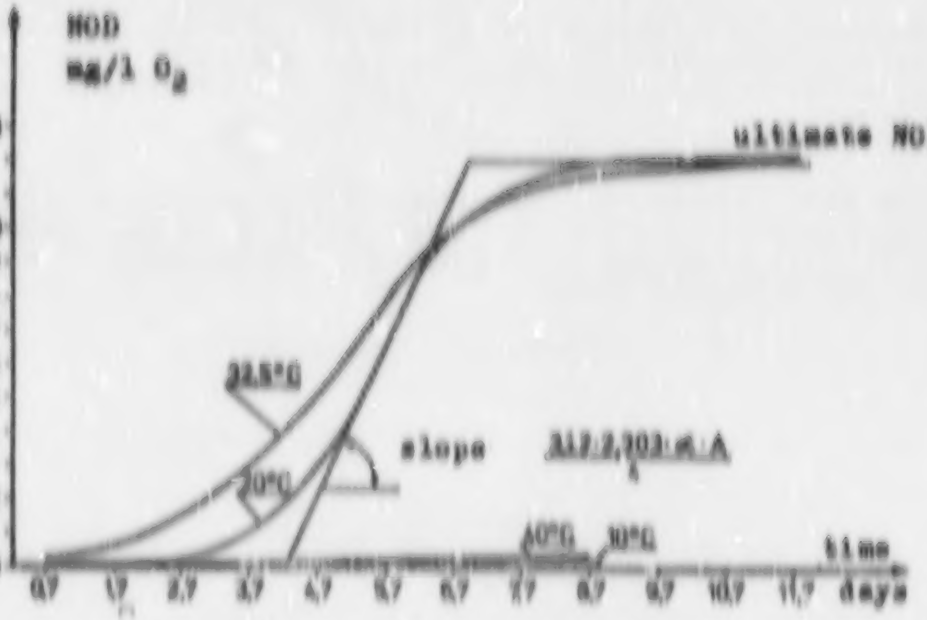


Fig. 38. Oxygen demand for nitrification of the I stage for Vistula water. March, 1974. The initial concentration of ammonia A = 3,8 mg/l N

$$\frac{dBOD}{dt} = \frac{2.303 \cdot 3.22 \cdot \alpha \cdot A}{4}$$

The slope of a straight line approximates the slope of a curve the best, when calculated for $t = t_1$, because just this point is an inflection point of a curve.

Oxygen balance in river waters depends on the rate of oxygen consumption and on the rate of reaeration. If the rate of oxygen consumption does not depend on time what applies for the time interval in which the curve of oxygen consumption is approximately a straight line oxygen concentration aims to the balance defined by the expression:

$$\frac{3.22 \cdot 2.303 \cdot \alpha \cdot A}{4} = D \cdot k_2 \cdot 2.303$$

it results from the formula for the rate of reaeration

$$\frac{dD}{dt} = 2.303\ k_2 \cdot D$$

Finally, oxygen conditions aim to the equilibrium when oxygen deficit is equal to:

$$D = \frac{0.803 \cdot A \cdot \alpha}{k_2}\ \mathrm{mg/l\ O_2}$$

For example in the water of concentration equal to 3.0mg/l $N-NH_3$ D.O. deficit is as follows (conditions $k_2 = 0.41\ d^{-1}$; $\alpha = 0.15\ d^{-1}$ at 10°C; 0.63 at 20°C; 0.37 at 32.5°C; 0.12 at 40°C)

temp. °C	D mg/l O_2
10	0.9
20	3.8
32.5	2.2
40	0.7

Taking into consideration a possible influence of heating on nitrification and oxygen balance in the Vistula river, three periods can be distinguished: a) in winter when water temperature is close to 0°C and water is covered with ice; b) in summer when natural water - temperature is about 20°C; c) in autumn and in spring when water temperature is about 10 °C.

In winter the discharge of heated water may cause an increase of water temperature in the river by several degrees and release a certain section of river from ice cover. The investigations show that at temperatures up to 10°C the process of nitrification is very slow; both a decrease of ammonia concentration and of oxygen consumption in the process of nitrification are rather small.

Simultaneous diminuation of an ice cover improves the aeration conditions in the water of a river.

In summer the influence of heating upon nitrification will also be small, which is due to two reasons: 1) in this period the ammonia concentration in waters of the Vistula river near Kozienice is usually very small, 2) heating of water by several degrees above 20 °C will not affect oxygen consumption in a large extent because α factor has its extreme at 20 °C.

The largest influence of heating on the process of nitrification may appear in spring and in fall. In such periods the ammonia concentration may be high, an increase of temperature by several degrees within the range of temperatures from 10 °C to 20 °C respectively can accelerate this process. It can also cause a more rapid oxidation of ammonia and can accelerate oxygen consumption.

SECTION 7

THE METHOD FOR PERMISSIBLE RIVER WATER TEMPERATURE CALCULATION BASED ON THE OXYGEN CRITERIA

CRITICAL OXYGEN DEFICIT CALCULATION

Excessive organic pollution load discharged into the river can cause a harmful oxygen deficit in the receiver water. The temperature increase accelerates oxygen uptake process and can cause additional oxygen depletion. The oxygen balance in the river may be controlled by means of either reduction of organic load discharged into the river or reduction of heat discharged from the power plant.

Oxygen deficit can be calculated from the following equation:

$$D = \frac{k_1 \cdot L}{k_2 - k_1} \left(10^{-k_1 t} - 10^{-k_2 t} \right) + D_0 \cdot 10^{-k_2 t} \qquad (1)$$

which is a transformed Streeter Phelps's equation, where:

k_1 = oxygen uptake rate coefficient

k_2 = reaeration rate coefficient

L = final BOD

D_0 = initial oxygen deficit

The time t_{cr}, corresponding to the critical, i.e. maximum oxygen deficit can be calculated from the equation:

$$t_{cr} = \frac{1}{k_2 - k_1} \log\left(\frac{k_2}{k_1} - \frac{k_2 (k_2 - k_1) \cdot D_0}{k_1^2 \cdot L_0} \right) \qquad (2)$$

where:

L_0 = initial BOD of the river water after mixing with wastes.

The following data are necessary for the calculation:

D_0 - initial oxygen deficit at the cross-section of river, in which the waste waters are fully mixed with river water .

L_0 = total initial BOD

$k_1, k_2, \Theta_1, \Theta_2$

D_0 and L_0 can be calculated from the equations:

$$D_0 = \frac{D_r \cdot Q_r + D_w \cdot Q_w}{Q_r + Q_w} \text{ mg/l } O_2 \tag{3}$$

$$BOD_5 \text{ mixed} = \frac{BOD_r \cdot Q_r + BOD_w \cdot Q_w}{Q_r + Q_w} \text{ mg/l } O_2 \tag{4}$$

where index "r" denotes river water
and "w" denotes waste water.

The final BOD (L_0) is related to BOD_5:

$$L_0 = \frac{BOD_5 \text{ mix}}{1 - 10^{-5k_1}} \tag{5}$$

The calculation of oxygen deficit for different temperatures and values of BOD_5 allows for the determination of the maximum permissible temperature of river water in relation to minimum oxygen concentration required. Such a calculation consists of the subsequent approximations which require many calculations. An attempt to formulate a direct relation enabling permissible temperature calculation, was made to simplify the necessary computations.

FORMULATION OF OXYGEN CRITERION RELATION ENABLING PERMISSIBLE TEMPERATURE CALCULATION

On the base of Streeter Phelp's equations, the equations for direct calculation of permissible temperature as function of organic load and tolerated minimum oxygen concentration are suggested.

The temperature range from 25 °C to 35 °C was considered. The temperature of 35 °C is a maximal temperature permissible for other reasons than oxygen conditions, e.g. for the protection of biocenosis of a river. Temperature of 25 °C is the natural river water temperature often occurring in summer time in Poland.

The simplifying assumption was made, that the temperature during the biochemical decomposition of organic matter in the river is constant. It is roughly true if the temperature of river water depends on the natural climatic conditions only, but in the case of heated water discharge from power plant such assumption does not correspond to the real situation. In fact, the temperature below the power plant decreases along the river course due to the mixing of heated water with river water and to transferring of heat into atmosphere. This continuous decrease of temperature complicates the calculations, so the simplifying assumption was made, that the river water temperature is constant along the river section under consideration, and that it equals to the temperature of water at the point of thermal water discharge with assumption of full mixing. In fact, the temperature in the vicinity of heated water discharge is higher, and downstream is lower than the temperature in such a way assumed, which approximates this assumption to the average real temperature.

In following part of paper the equations were deducted for two cases: 1) 100 % saturation of river water with oxygen at the initial point of the river section under consideration and 2) with assumption of initial oxygen deficit.

Case No 1

If initial oxygen deficit D_0 equals to zero, the Streeter-Phelps equation

$$D_{cr} = L_0\left(\frac{k_2}{k_1}\right)^{-k_2/k_2-k_1} \cdot \left(1 - \frac{D_0}{L_0} \cdot \frac{k_2-k_1}{k_1}\right)^{-k_1/k_2-k_1}$$

is transformed to

$$D_{cr} = L_0\left(\frac{k_2}{k_1}\right)^{-k_2/k_2-k_1} = L_0 \cdot f^{-f/f-1} \qquad (6)$$

where $f=k_2/k_1$. The term $L_0 \cdot f^{-f/f-1}$ is discontinuous when $f = 1$,

In such a case

$$D_{cr} = \lim_{f \to 1} L_0 \cdot f^{-f/f-1} = \frac{L_0}{e}$$

If C denotes minimum oxygen concentration requested at the critical point, the following condition must be satisfied:

$$C_s - C \geq D_{cr} \tag{7}$$

where C_s denotes solubility of oxygen in water at a given temperature.

The formulas (6) and (7) may be rearranged:

$$C_s - C \geq L_0 \cdot f^{-f/f-1} \qquad f \neq 1$$

$$C_s - C \geq L_0/e \qquad f = 1$$

For maximum permissible temperature calculation we can consider the equation:

$$C_s - C = L_0 \cdot f^{-f/f-1} \tag{8}$$

The term $f^{-f/f-1}$ may be approximated:

if $0{,}5 \leq f \leq 2{,}5$ if $2{,}5 \leq f \leq 10$

$$f^{-f/f-1} = \frac{3}{4} \cdot \frac{1}{f+1} \qquad f^{-f/f-1} = \frac{0{,}8847}{f+1{,}3969} \tag{9}$$

The value of oxygen concentration in water in equilibrium with air at temperature T is approximatively given by Hatfield's (41) equation:

$$C_s = \frac{0{,}678(P - p)}{T + 35} \tag{10}$$

where:

P - atmospheric pressure, mm Hg
p - water vapor pressure, mm Hg
T - temperature, ^{0}C

We can replace this equation by an approximated one:

$$C_s = \frac{0,678(P-\mu_T)}{T-30+65} = \frac{\frac{0,678(P-\mu_T)}{65}}{1+\frac{T-30}{65}} \cong \frac{0,678(P-\mu_T)}{65}\left(1-\frac{T-30}{65}\right) =$$

$$= -\frac{T\cdot 0,678(P-\mu_T)}{65^2} + \frac{95\cdot 0,678(P-\mu_T)}{65^2}$$

This may be written as:

$$C_s = a\cdot T + b \quad \text{where} \quad a = -\frac{0,678(P-\mu_T)}{65^2}$$

$$b = \frac{95\cdot 0,678(P-\mu_T)}{65^2}$$

As μ_T depends on the temperature, the calculation a and b as constants follows to some error. This error may be neglected, if we draw the straight line aT+b through two points at the ends of temperature range under consideration, i.e. corresponding to 25 °C and 35 °C. Concentration of oxygen at saturation of water with air amounts to 8,33 and 6,95 mg/l, respectively.

The equation of such straight line is:

$$C_s = T\cdot\frac{C_2-C_1}{T_2-T_1} + \frac{C_1-C_2}{T_2-T_1}\cdot T_2 + C_2 = T\cdot\frac{6,95-8,33}{35-25} +$$

$$+\frac{8,33-6,95}{35-25}\cdot 35 + 6,95 = -0,137\,T + 11,745$$

$$C_s = -0,137\,T + 11,745 \qquad (11)$$

From equations 9 and 11 and 8 we can deduct:

if $0,5 \leq f \leq 2,5$

$$- 0,137\ T + 11,745 - C = L_0 \cdot \frac{d}{4} \cdot \frac{1}{f+1} \qquad (12)$$

if $2,5 \leq f \leq 10$

$$- 0,137\ T + 11,745 - C = L_0 \cdot \frac{0,8047}{f+1,5969} \qquad (13)$$

The parameter f depends on temperature as follows:

$$f_{(T)} = \frac{k_{2(20^{\circ}C)} \cdot \Theta_2^{(T-20^{\circ})}}{k_{1(20^{\circ}C)} \cdot \Theta_1^{(T-20^{\circ})}} \qquad (14)$$

For the best approximation of f as linear function of T, the reference temperature equal to 30° is most appropriate. Denoting $f_{30^{\circ}}$ as f_0

$$f_0 = \frac{k_{2(20^{\circ})}}{k_{1(20^{\circ})}} \cdot \left(\frac{\Theta_2}{\Theta_1}\right)^{10}$$

The values of Θ_2 and Θ_1 have the form of $1 + x$, where x is a small number of several hundredth (e.g. $\Theta_1 = 1,047$), so we can approximate the term Θ_2/Θ_1 as follows:

$$\frac{\Theta_2}{\Theta_1} \cong 1 + \Theta_2 - \Theta_1$$

The accuracy of such transformation is given below for typical values of $\Theta_2 = 1,024$ and $\Theta_1 = 1,047$

$$\frac{\Theta_2}{\Theta_1} = \frac{1,024}{1,047} = 0,978$$

$$1 + \Theta_2 - \Theta_1 = 1 + 1,024 - 1,047 = 0,977$$

The difference does not exceed 0,001.
So the term θ_2/θ_1 can be written as:

$$\frac{\theta_2}{\theta_1} \cong 1 + \alpha , \quad \text{where } \alpha = \theta_2 - \theta_1 \tag{15}$$

and equation (14) as

$$f_{(T)} = f_0 \cdot \left(\frac{\theta_2}{\theta_1}\right)^{T-30} \tag{16}$$

$$f_{(T)} = f_0 \left(1 + \alpha\right)^{T-30}$$

The term $\left(1 + \alpha\right)^{T-30}$ can be replaced by Newton's series expansion:

$$f_{(T)} = f_0 \left[1 + \alpha \binom{T-30}{1} + \alpha^2 \binom{T-30}{2} + \alpha^3 \binom{T-30}{3} + \ldots\ldots\ldots \right]$$

For the typical values of about 0,03 and temperature in the range from 25 °C to 35 °C, all terms in the series except $1 + \alpha\binom{T-30}{1}$, may be neglected. So

$$f_{(T)} \cong f_0 \left[1 + \alpha\left(T-30\right)\right] \tag{17}$$

The following example shows the accuracy of such approximation if the temperature amounts to 25 °C and α equals from 1,024 − 1,047 = − 0,023

$$\left(1 + \alpha\right)^{T-30} = 0,977^{-5} = 1,123$$

$$1 + \alpha\left(T-30\right) = 1 - 0,023\left(-5\right) = 1,115$$

The error equal to 0,7 % may be neglected. If temperature comes closer to 30 °C, the error will be lower.
Substitution of equation (12) into (17) if $0,5 \leq f \leq 2,5$ follows to the following equations:

$$- 0{,}137\, T + 11{,}749 - C = \frac{3}{4} \cdot L_0 \frac{1}{1 + f_0 \left[1 + \alpha (T-30)\right]} \qquad (18)$$

or:

$$- 0{,}137\, T + 11{,}749 - C = \frac{3}{4} \cdot L_0 \frac{1}{1+f_0} \cdot \frac{1}{1 + \frac{\alpha f_0 (T-30)}{1+f_0}}$$

As the term $\frac{\alpha f_0 (T-30)}{1 + f_0}$ is much smaller than 1, (at the typical values $\alpha = - 0{,}023$, $T-30 < 5$, $f \leq 2{,}5$

$$\frac{\alpha\, f_0 (T-30)}{1 + f_0} \leq 0{,}08$$

we can replace equation (18) by the approximate one:

$$- 0{,}137\, T + 11{,}749 - C \cong \frac{3}{4} \cdot L_0 \frac{1}{1+f_0} \left(1 - \frac{\alpha f_0 (T-30)}{1 + f_0}\right)$$

Rearranging of the last equation follows to

$$T_d = \frac{C - 11{,}749 + \frac{0{,}75\, L_0}{(1 + f_0)^2} (1 + f_0 + 30\, \alpha f_0)}{\frac{0{,}75\, L_0 \alpha f_0}{(1 + f_0)^2} - 0{,}137}$$

$$T_d = \frac{11{,}749 - C - \frac{0{,}75\, L_0}{(1 + f_0)^2} (1 + f_0 + 30\, \alpha f_0)}{0{,}137 - \frac{0{,}75\, L_0 \alpha \cdot f_0}{(1 + f_0)^2}} \qquad (19)$$

Analogically, substitution of equation (13) to (17) follows to: at $2{,}5 \leq f \leq 10$

$$-0{,}137\,T + 11{,}745 - C = L_0 \frac{0{,}0047}{1{,}5969 + f_0\left(1 + \alpha(T-30)\right)}$$

and approximating as formerly

$$-0{,}137\,T + 11{,}745 - C = L_0 \frac{0{,}0047}{1{,}5969 + f_0} -$$

$$-\frac{0{,}0047\,\alpha \cdot f_0 \cdot T \cdot L_0}{(1{,}5969 + f_0)^2} + \frac{0{,}0047\,\alpha\, f_0 \cdot L_0 \cdot 30}{(1{,}5969 + f_0)^2}$$

$$T_d = \frac{-11{,}745 + C + \frac{0{,}0047\,L_0}{(1{,}5969+f_0)^2}\left[1{,}5969+f_0+30\,\alpha \cdot f_0\right]}{-0{,}137 + \frac{0{,}0047\cdot\alpha \cdot f_0 \cdot L_0}{(1{,}5969 + f_0)^2}}$$

$$T_d = \frac{11{,}745 - C - \frac{0{,}0047\,L_0}{(1{,}5969+f_0)^2}\left(1{,}5969+f_0+\alpha \cdot f_0 \cdot 30\right)}{0{,}137 - \frac{0{,}0047\,\alpha \cdot f_0 \cdot L_0}{(1{,}5969 + f_0)^2}}$$

$$T_d = \frac{11.749 - C - \frac{0.889\ L_0}{(1.397+f_0)^2}\ (1.397+f_0+\alpha \cdot f_0 \cdot 30)}{0.137 - \frac{0.889\,\alpha \cdot f_0 \cdot L_0}{(1.397+f_0)^2}} \qquad (20)$$

Case No 2 initial oxygen deficit is not equal zero

The exact equation describing permissible temperature based on Streeter Phelps's equation would be very complicated if the initial oxygen deficit was unequal zero. So, the formal operation is applied, consisting of the assumption that at a certain point t_1, lying upstream from the initial considered part of the river a complete BOD occurs (L_1), greater than L_0 and a deficit equalling zero (fig.39). According to the Streeter Phelps equation at the starting point a deficit is formed which is equal to the former initial deficit, and L_1 decrease to L_0. At the assumption that at point t_1 (upstream from the initial point of the river section under consideration) oxygen deficit equals zero and total BOD equals L_1, the oxygen curve below the starting point runs in accordance with the Streeter Phelps curve, analogically as at the assumption that total BOD and oxygen deficit at starting point are equal L_0 and D_0.
It should only be assumed that:

$$L_1 = L_0\left[1 - (f-1) \cdot \frac{D_0}{L_0}\right]^{\frac{1}{1-f}} \qquad (21)$$

Then

$$D_{cr} = L_1 \cdot f^{-f/f-1} \qquad \text{for } f \neq 1$$

$$D_{cr} = L_1 \cdot \frac{1}{e} \qquad \text{for } f = 1$$

In such a case we calculate the permissible temperature from formulas 19 and 20, substituting value L_1 instead of L_0. However, in the case when the initial deficit is large in comparison with L_0, the oxygen curve on the considered part does

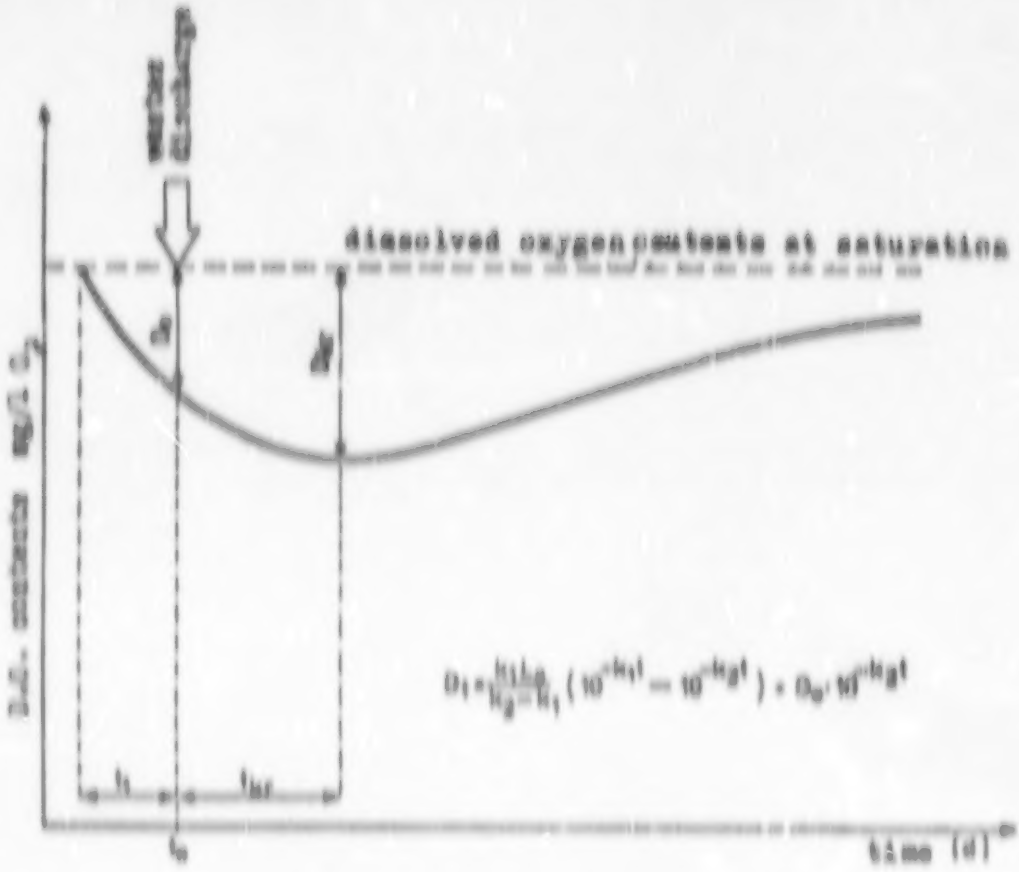


Fig. 39. Oxygen sag curve in river water

L_0 = initial BOD
L_1 = BOD presumed at moment t_1
t_1 = moment t_1 above initial point
D_0 = initial oxygen deficit
D_{kr} = critical oxygen deficit

not have a minimum, which occurs above the initial point between t_0 and t_1. This occurs in the case when critical time calculated from:

$$t_{cr} = \frac{1}{k_2 - k_1} \log\left[\frac{k_2}{k_1}\left(1 - \frac{D_a}{L_0} \cdot \frac{k_2 - k_1}{k_1}\right)\right] = \frac{1}{k_2 - k_1} \cdot$$

$$\log\left\{f\left[1 - \frac{D_a}{L_0}\left(f - 1\right)\right]\right\} = \frac{1}{k_1} \cdot \frac{1}{f-1} \log\left\{f\left[1 - \frac{D_a}{L_0}\left(f-1\right)\right]\right\}$$

has a negative value. Thus the calculation of oxygen deficit for a given sector is justified when $t_{cr} > 0$, or:

$$\frac{1}{k_1} \cdot \frac{1}{f-1} \log\left\{f\left[1 - \frac{D_a}{L_0}\left(f - 1\right)\right]\right\} > 0$$

in the case when $f > 1$ we can omit $\frac{1}{k_1} \cdot \frac{1}{f-1}$

$$\log\left\{f\left[1 - \frac{D_a}{L_0}\left(f - 1\right)\right]\right\} > 0$$

$$f\left[1 - \frac{D_a}{L_0}\left(f - 1\right)\right] > 1$$

$$1 - \frac{D_a}{L_0}\left(f - 1\right) > \frac{1}{f} \; ; \qquad - \frac{D_a}{L_0}\left(f - 1\right) > \frac{1-f}{f}$$

$$\frac{D_a}{L_0} \leqslant \frac{1}{f}$$

Analogical calculation for $f < 1$ also leads to the condition:

$$\frac{D_p}{L_0} \leq \frac{1}{f}$$

and for $f = 1$ the expression for t_{cr} is discontinuous, but convergent to the limit:

$$t_{cr} = \lim_{f \to 1} \frac{1}{k_1} \cdot \frac{1}{f-1} \log\left\{ f\left[1 - \frac{D_p}{L_0} (f-1) \right] \right\} = \frac{1}{2,3\ k_1} \left(1 - \frac{D_p}{L_0} \right)$$

condition $t_{cr} \geq 0$ thus leads to the condition:

$$\frac{1}{2,3\ k_1} \left(1 - \frac{D_p}{L_0} \right) \geq 0$$

thus $1 \geq \frac{D_p}{L_0}$, which is an equivalent to the former condition

$$\frac{1}{f} \geq \frac{D_p}{L_0}$$

Substituting for f an expression from equation 17 we obtain

$$\frac{D_p}{L_0} \leq \frac{1}{f_0 \left[1 + \alpha (T-30) \right]}$$

The solution of inequality depends on the sign of the expression $1 + \alpha (T-30)$. In the considered range of temperature from 20 to 35 °C it can be written that $-10 \leq T-30 \leq +5$. The value α is usually negative and much higher than $-0,2$ (which is confirmed by all accessible data).
Thus:

$$\alpha (T-30) \geq -0,2 \cdot 5$$
$$\alpha (T-30) \geq -1$$
$$1 + \alpha (T-30) \geq 0$$

In such a case:

$$\text{inequality} \quad \frac{D_a}{L_a} \leq \frac{1}{f_a\left[1 + \alpha(T-20)\right]}$$

can be transformed into (at the assumption $\alpha < 0$):

$$T \geq \frac{D_a f_a - L_a}{-\alpha D_a f_a} + 20\ ^{\circ}C$$

Critical oxygen deficit will occur only when the value T will be higher than

$$\frac{D_a f_a - L_a}{-\alpha D_a f_a} + 20\ ^{\circ}C \qquad (22)$$

In a special case when $\alpha = 0$, f is unchangeable, thus the condition for the occurrence of critical deficit is:

$$\frac{1}{f_a} \geq \frac{D_a}{L_a} \qquad \text{or} \qquad \frac{L_a}{D_a} \geq f_a \qquad (23)$$

This is the first of the two conditions for temperatures. If from this condition it follows that $T \geq 35\ ^{\circ}C$, this means that in the Vistula in the range of temperatures even up to 35 °C the oxygen deficit greater than the initial one will not occur. In such a case it should be stated that heating of water even up to 35 °C does not cause oxygen deficit in the river and that the oxygen conditions cannot be a criterion for determining a permissible temperature in the river.

If the temperature calculated from the formula 22 will be lower than 35 °C, a second condition should be calculated from formulas 19 and 20, substituting L_1 as in equation (21) instead of L_a:

$$L_1 = L_a\left[1 - (f-1)\cdot\frac{D_a}{L_a}\right]^{\frac{1}{1-f}} \qquad \text{for } f \neq 1$$

or:
$$L_1 = L_0 \cdot e^{D_0/L_0} \qquad \text{for } f = 1$$

This expression is in a slight degree dependent on f, and for this reason, for simplification, in the place of $f_{(T)}$, $f_0 = f_{20°C}$ was adapted.

Summarising, the calculation of the permissible temperature of water according to the oxygen criterion is as follows:

Initial data:

L_0 = total BOD of water at the beginning of the considered sector (in the case of wastes, after assuming a full mixing with the river water) in mg/l O_2

$$L_0 = \frac{BOD_5}{1 - 10^{-5k_1}} \qquad (5)$$

D_0 = initial oxygen deficit at the mixing point in mg/l O_2
k_1 and k_2 at 20 °C
k_2 can be calculated from the formula:

$$k_2 = 1{,}72\,\frac{U^{0{,}5}}{H^{1{,}5}} \qquad (24)$$

where:

U = velocity of water flow in the river in m/s
H = depth of the river in m
k_1 = should be calculated from the results of tests θ_1 and θ_2

Additional calculations:

$$f_0 = \frac{k_{2(20°)}}{k_{1(20°)}} \cdot \left(\frac{\theta_2}{\theta_1}\right)^{10} \qquad (25)$$

$$\alpha = \theta_2 - \theta_1$$

$$L_1 = L_0\left[1 - (f_0 - 1)\frac{D_0}{L_0}\right]^{\frac{1}{1-f_0}} \qquad \text{for } f \neq 1$$

$$L_1 = L_0 \cdot e^{D_0/L_0} \qquad \text{for } f = 1$$

Calculation of condition 1:

$$T_1 = \frac{D_0 f_0 - L_0}{-\alpha D_0 f_0} + 30\ ^{\circ}C \qquad (22)$$

If $T_1 \geq 35^{\circ}C$, the critical deficit at the considered sector does not occur. Oxygen conditions in this area are better at the initial point. If $T_1 < 35^{\circ}C$ then the temperature should be calculated according to condition 2.

Calculation of condition 2:

$$T_2 = \frac{11{,}745 - C - \dfrac{0{,}73\ L_1 (1 + f_0 + 30\alpha f_0)}{(1 + f_0)^2}}{0{,}137 - \dfrac{0{,}73\ L_1\ f_0 \alpha}{(1 + f_0)^2}} \qquad (19)$$

for $0{,}5 \leq f \leq 2{,}5$; and

$$T_2 = \frac{11{,}749 - C - \dfrac{0{,}889\ L_1}{(1{,}597 + f_0)^2}\left[1{,}597 + f_0 + 30\alpha f_0\right]}{0{,}137 - \dfrac{0{,}889\,\alpha \cdot f_0 L_1}{(1{,}597 + f_0)^2}} \qquad (20)$$

for $2{,}5 \leq f \leq 10$

From the point of view of oxygen criterion the permissible temperature should be higher one among T_1 and T_2 calculated.

EXAMPLARY CALCULATION OF PERMISSIBLE TEMPERATURE

Oxygen deficit and permissible temperature of heated water in the Vistula downstream from the Kozienice power plant was calculated.

Initial data:

D_0 = 1.37 mg/l O_2 e.g. 15 % saturation at 20 °C
$k_{1(20°C)} = 0,1$; $k_{2(20°C)} = 0,51$; $\Theta_1 = 1,024$; $\Theta_2 = 1,024$;
BOD_5 of the river in the range 2 – 10 mg/l O_2; $\alpha = 0$.

Calculation of oxygen deficit and critical time

The changes of the factors k_1 and k_2 at different temperatures in relation to Θ values assumed are as follows:

Factor	Temperature °C			
	20	25	30	35
k_1	0,10	0,1126	0,1268	0,1427
k_2	0,51	0,574	0,647	0,728

The values of oxygen deficit and critical time for different temperatures calculated on the basis of formulas 1 and 2 are shown in tabl. 41.

Calculation of permissible temperature

$$f_0 = \frac{k_{2(20°C)}}{k_{1(20°C)}} \cdot \left(\frac{\Theta_2}{\Theta_1}\right)^{10} = 5,1$$

L_1 calculated from the formula:

$$L_1 = L_0\left[1 - (f - 1)\frac{D_0}{L_0}\right]^{\frac{1}{1-f_0}}$$

Table 41. Oxygen deficit and critical time values for Vistula river water at various temperatures

No				1	2	3
BOD_5	mg/l O_2	2	4	6	8	10
L_a	mg/l O_2	2,92	5,85	8,77	11,70	14,62
	t_{cr}	-	-	0,643	1,033	1,212
20 °C	D_{cr}	n.o.[x)]	n.o	1,48	1,809	2,168
	C	-	-	7,67	7,341	6,982
	t_{cr}	-	-	0,570	0,917	1,077
25 °C	D_{cr}	n.o.	n.o.	1,48	1,809	2,168
	C	-	-	6,84	6,51	6,15
	t_{cr}	-	-	0,5066	0,815	0,956
30 °C	D_{cr}	n.o.	n.o.	1,48	1,809	2,168
	C	-	-	6,12	5,79	5,43
	t_{cr}	-	-	0,450	0,724	0,849
35 °C	D_{cr}	n.o	n.o	1,48	1,809	2,168
	C	-	-	5,47	5,14	4,783

x) n.o. = not observed

obtaining results:

BOD_5 mg/l O_2	6	8	14
L_0	8,77	11,70	14,62
L_1	11,29	13,72	16,46

The calculation of the permissible temperature begins with the checking of condition 1, having in this case (when $\alpha = 0$) the following form $L_0/D_0 = f_0 > 0$. For all values L_0 from 8.77 to 14,62 this condition is fulfilled. For BOD_5 equalling 2 and 4 mg/l O_2 the calculations were not done, because at this level of pollution the critical deficit does not occur. Because condition 1 does not provide any restrictions of temperature the condition 2 was calculated from the formula 29, which in this case, when $\alpha = 0$ has the following form

$$T_d = \frac{11{,}749 - C - \dfrac{0{,}889\ L_1}{f_0 + 1{,}3969}}{0{,}137}.$$

The results of calculation of T_d for different degrees of pollution (L_1) and different permissible dissolved oxygen concentrations (C) are shown in tabl. 42

Table 42. Permissible temperature T_d values, calculated for Vistula river water

No	L_1	C	T_d
1	11,29	6	31,09
		7,9	20,14
2	13,72	5,5	32,39
		7,0	21,40
3	16,46	5,0	33,36
		6,5	22,41

The obtained results of permissible temperatures are shown on a graph (fig.40), on which we can see the dependence of oxygen concentration on temperature calculated according to the Streeter Phelps formula (tabl.41). Within the range of temperatures of 25 - 35 °C a large agreement was obtained.

From these graphs it can be seen that with the assumed oxygen deficit D_a = of inflowing water, at $BOD_5 = 10$ mg/l O_2, the water temperature can arise up to 33 °C without a decrease of oxygen below 5 mg/l O_2. Because the Vistula pollution in the vicinity of Kozienice rarely exceeds $BOD_5 = 10$ mg/l O_2, it can be stated that in present situation the Vistula water will not be subject to lethal oxygen deficit.

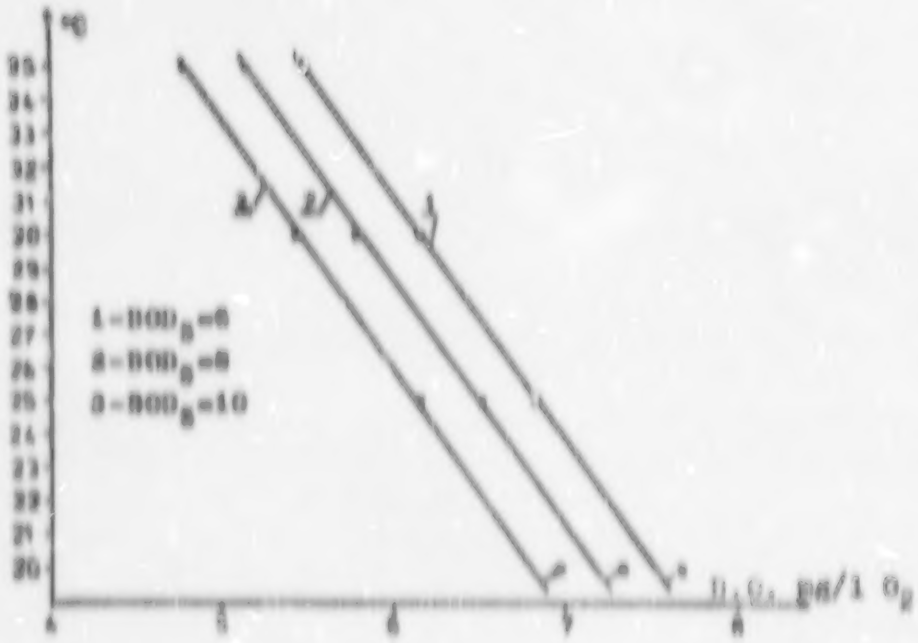


Fig.40. D.O. contents at critical point depending on temperature of Vistula river water below Kozienice power station, calculated for various pollutant levels.

$k_{1\ 20°C} = 0,1$; $\theta_1 = 1,024$; $D_0 = 1,37$ mg/l O_2
$k_{2\ 20°C} = 0,31$; $\theta_2 = 1,024$;
The straight lines are drawn according to the equation 29 , and points "o" are marked according to the table 41.

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